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FINAL REPORT

for Contract #NAS2-7651

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WATER VAPOR DIFFUSION MEMBRANE DEVELOPMENT

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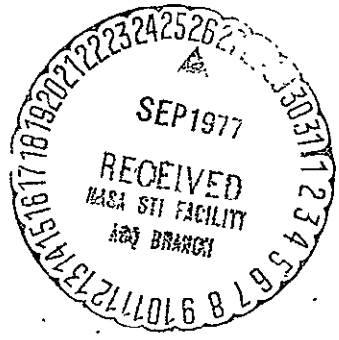

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I. SUMMARY AND CONCLUSIONS

The development of the water vapor diffusion technique has been centered on its application to reclaim potable water from wastewater on-board spacecraft on missions of extended duration. This report examines another application of the technique whereby the permeated water vapor is vented to space vacuum to alleviate on-board waste storage and provide supplemental cooling. Such an application is highly suitable for space-craft on missions of short duration, such as the Space Shuttle.

To distinguish between the two applications, this report will refer to the water-reclaiming system as the VD-WR or Vapor Diffusion - Water Reclamation and the heat-rejecting system as the VD-HR or Vapor Diffusion-Heat Rejection.

The work reported herein was performed under contract #NAS2-7681 with NASA-Ames Research Center. It deals primarily with the VD-HR as it applies to the Space Shuttle. A stack configuration was selected, designed and fabricated. An asymmetric cellulose acetate membrane, used in reverse osmosis application was selected. A special spacer was designed to enhance mixing and promote mass transfer. A skid-mount unit was assembled from components used in the bench unit although no attempt was made to render it flight-suitable.

The operating conditions of the VD-HR were examined and defined. No chemical pretreatment or particulate prefiltration of the wastewater charge is required. An evaporator temperature of 333-347^{o}K (145-165^{o}F) is recommended. The actual operating temperature is expected to be defined by the accessible on-board heat source, most likely the cooling loop from the fuel cells, and the rate of over-board venting and supplemental cooling desired.

A heating-fluid loop is recommended to effect heat exchange between

the on-board heat source and the evaporator compartments of the stack. Two magnetic drive pumps would be used to continuously recirculate the heating-fluid and the charge at 0.25m/sec (0.83ft/sec) and 0.3m/sec (0.99ft/sec), respectively. These pumps represent the only moving parts of the system. The electrical energy required to operate them, estimated as 24.4 watts, represents the bulk of the energy requirement of the system.

A 60-day continuous test was carried out. Operating parameters were deliberately varied throughout to subject the system to extreme conditions. The membranes, which are expected to be the weakest components of the system, perform very well throughout the test. No membrane rupture and no unusual flux decay was observed.

In addition, a tentative design for a flight-suitable VD-HR unit was made. Estimation of the weight and volume penalties of such a unit was obtained and compared with on-board waste storage. The comparison is favorable even without any attempt to incorporate flight-worthy components.

The recovery of part or all of the water for on-board reuse involves a different design. Its feasibility has been demonstrated by various investigators, notably Hamilton Standard Division of United Aircraft Corporation, now United Technologies. A design by Ionics, Inc. of such a VD-WR unit is presented in the Appendix of this report.

The technological development in this area may include the following:

Phase I	Development, design and fabrication of preprototype for extended tests.
Phase II	Design and fabrication of prototype mission kit for the Space Shuttle on special missions.
Phase III	Incorporation of unit into the permanent Space Shuttle Systems.
Phase IV	Development, design and fabrication of alternative water reclaiming subsystem.
Phase V	Design and fabrication of prototype for complete water reclamation for Space Station.

II. INTRODUCTION

During space missions of extended duration limitations of launch weight and on-board storage volume preclude the carrying of potable water to meet drinking and sanitation needs of the astronauts. A closed system for the recovery of potable water from spacecraft wastewater (human urine and washwater) is, therefore, required.

Several systems for the reclamation of potable water from wastewater have been successfully demonstrated. The various distillation techniques have proved to be the most successful of these systems from the standpoint of economy and efficiency. The Vapor Diffusion-Water Reclamation System (VD-WR) is essentially a vacuum distillation technique employing a selective polymeric film as a liquid-vapor phase separator. Its development is primarily the work of Hamilton Standard and of Ionics, Incorporated.

Hamilton Standard built a laboratory prototype under contract #NAS1-5312 for NASA-Langley Research Center in 1966, and made several optimization studies and improvements in a subsequent contract, #NAS1-7170, but several problems were left unsolved and several components exhibited marginal performance.

Subsequent efforts to improve upon these components led to the work performed under the present contract #NAS2-7651.

III. THE VD-WR TECHNOLOGY

1. Principle

The principle of the Vapor Diffusion-Water Reclamation (VD-WR) Technique is illustrated in Figure 1. A charge is introduced into the evaporator compartment and heated to a temperature T_1. Evaporation occurs, the vapor diffuses through the gap and is condensed at the condenser compartment maintained at T_2, below its saturation temperature. Two phase separators prevent the mixing of the liquid and the vapor as shown in the diagram. The temperature gradient, (T_1 less T_2) maintains a vapor partial pressure gradient across the diffusion gap and this is the driving force in the system.

At steady state, heat is continuously supplied to the evaporator and removed from the condenser. Charge constituents with low vapor pressures, such as water, are preferentially removed from the charge and collected as the condensate. The exact mechanism involved in the VD-WR is complex and varies with the particular design. The diffusion rate of the vapor through the gas gap is usually the most difficult to control. Effectively it becomes the overall rate-determining factor.

The evaporation rate may be improved by reducing the pressure using a vacuum pump or an aspirator. However, condensing the water vapor at low pressures is a problem. In addition, such a component will increase weight and power penalties. The tapping of space vacuum has not been successfully demonstrated and will lead to permanent losses of water vapor to outer space.

Higher selectivity of the system for water is achieved by the selection of a hydrophilic semi-permeable membrane as the charge-vapor phase separator. The membrane selectively retains waste solutes, certain organics and all microorganisms and passes essentially pure water. The results under Ionics Contract #NAS2-7651 showed that many

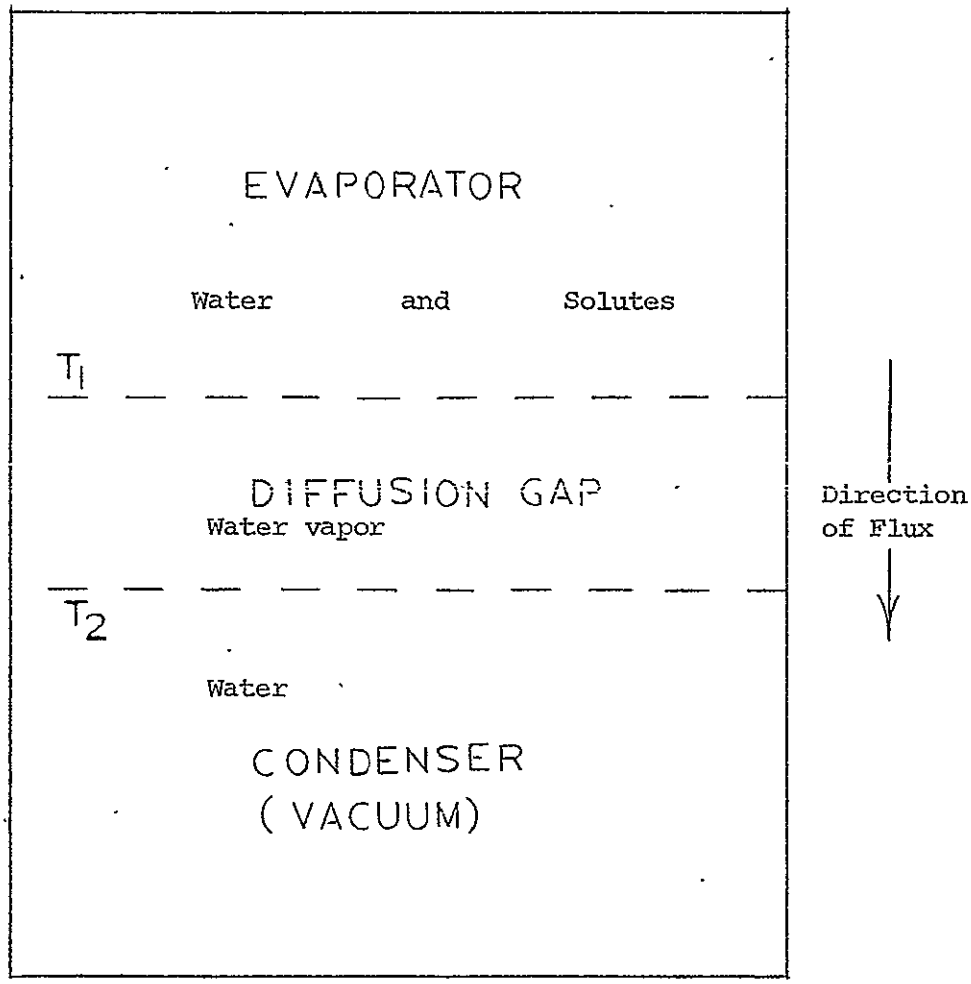


Figure 1. CONCEPTUAL ILLUSTRATION OF VD--WR

commercially available membranes for reverse osmosis application perform satisfactorily in terms of water flux and selectivity.

The introduction of the semipermeable membrane changes the mechanism of the process. Charge constituents selectively dissolve into the membrane. Evaporation occurs within the membrane and the vapor diffuses through the remaining portion of the membrane in a direction away from the charge. When sufficient agitation exists at the charge—membrane interface to minimize the resistance of boundary layers to mass transport, and when the impedance of the gas gap is minimized, the vapor diffusion rate through the membrane becomes the overall rate—limiting factor.

Various polymer films or diaphragms have also been successfully used as phase separators. Such films act as microfilters. Their performance is a function of the average pore size and the number of pores per unit area. However, when the overall porosity is sufficiently high as to render them attractive for VD-WR application, any applied vacuum will exceed their bubble point resulting in the passage of appreciable charge contaminants. This is facilitated by the presence of surface-active constituents such as soap or detergent.

2. The HSD Unit

A VD-WR unit was designed and fabricated by Hamilton Standard Division of United Aircraft in 1965. The unit was original in its use of a porous plate condenser which also acted as a vapor-distillate phase separator to achieve gravity insensitivity. It successfully produced 0.64 Kg (1.4 lbs) of water per hour. After treatment with activated charcoal the product water met potability standards of the USPHS and the SSB of NAS. The system also compared favorably to several other systems--distillation with pyrolysis, air evaporation, vapor compression distillation, reverse osmosis, and electrodialysis--ranking

first in fixed weight, third in expendable weights, third in energy requirement, and second in complexity. A subsequent contract led to several improvements, including a higher processing rate--1.1kg/hr (2.42 lb/hr).

Several components within the system exhibited marginal performance. Their improvement became the objective of the present program, Contract #NAS2-7651. At the center of the problem was the prevention of possible urea decomposition.

The initial approach called for lowering evaporator temperature and the addition of chromic acid to the urine charge to minimize urea decomposition into ammonia. However, if the evaporator temperature is lowered, a significant decrease in the processing rate will occur, entailing a corresponding increase in overall hardware volume and weight and necessitating a longer operation time. The chemical pretreatment raises the requirement for expendables, decreasing system effectiveness as mission duration increases. It also reduces membrane life and restricts the choice of membranes to those that are compatible with chromic acid. In addition, data on the interference by urea decomposition in the VD-WR are conflicting. Early work under the present contract, NAS2-7651 noted that HSD and other proponents of urine pretreatment did not publish actual measurements of such decomposition nor its subsequent interference. It was discovered that at elevated temperatures urea decomposition was actually quite low due to the overall buffering action of urine components, as well as the inactivation of the enzyme urease. It was also noted that with the proper selection of membrane, ammonia permeation can be minimized. The ammonia formed in the evaporator eventually equilibrated with the urine charge. The traces of organics and ammonia that permeated the membrane are vented to space vacuum together with the water vapor.

The HSD unit suffered from other problems, namely:

(i) the difficulty in maintaining a gap gas pressure above cabin pressure because of gas diffusion into the charge;

(ii) the contamination of the distillate water due to the formation of water channels connecting the condenser to the membrane;

(iii) the marginal performance of the cellophane and polyvinyl chloride membranes in terms of their life and structural integrity; and

(iv) the overall handling complications because of the delicate manner in which the components are held together.

In addition, the HSD unit was not gravity insensitive. The published flux depends on natural convection within the gas gap. In zero gravity environment the actual flux will be much lower unless forced convection is applied to enhance mixing.

IV. VD-HR FOR THE SPACE SHUTTLE

The Shuttle Orbiter carries the fuel cells that use cryogenically stored hydrogen and oxygen reactants to provide electrical power. Potable water is a by-product of this energy generation system, and, together, with a limited amount of pre-launch storage water, form the total water supply for the astronauts during the relatively short missions. This water supply will be used to meet the metabolic and personal hygiene needs of the astronauts as well as the housekeeping and spacecraft cooling needs; but it may not be enough. In addition, the wastewater generated must be stored on-board. Even if space contamination is not a consideration, overboard dumping of wastewater with solid entrainment will seriously interfere with various spacecraft systems and experiments, such as, optics, star sighting, etc. On-board wastewater storage presents a second major problem for the Orbiter.

Finally, the Orbiter may require supplemental cooling during periods of active payload deployment. The present design calls for a water-loop to remove excess heat from the crew cabin and various cabin avionics. A cabin heat interchanger transfers this heat to a Freon loop which also circulates through the fuel cells, the payloads and the aft avionics, bringing the total excess heat to the baseline radiators where it is radiated into space.

The VD-HR can be used to solve these problems. At least ninety per cent of the water in the waste may be removed via vapor diffusion through membrane phase-separator which selectively retains low vapor pressure constituents. This recovered water contains volatile organics and may be passed through charcoal filter cartridges to render it suitable for human usage. The excess recovered water is simply vented to space vacuum. The direct venting of water vapor and volatile organics is permissible because the various baseline systems (such as water flash

evaporation and feces inactivation) already dump water vapor and volatile organics. They are also not expected to seriously interfere with spacecraft instruments and experiments. In addition, the VD-HR, through the evaporation of water (and volatile organics), will consume the excess heat of the Freon loop, effectively providing supplemental cooling.

Thus, the VD-HR is tailored to meet the special needs of missions of short duration where it is not necessary to reclaim the treated water. While the omission of a condensing-collecting-post-treating subsystem will mean less engineering complications for the VD-HR than the VD-WR, the interfacing with space vacuum entails complications that require further studies.

V. WORK STATEMENT

The work performed under the contract is presented in the following paragraphs under six different tasks:

Task 1 Conversion to Stack Configuration

Task 2 Water Flux Studies

Task 3 Distillate Quality Studies

Task 4 Membrane Life Studies

Task 5 Additional Studies

A. Soap/Detergent Studies

B. Material Balance Studies

Task 6 Fabrication and testing of the Skid-Mount Unit

Task 1 Conversion to Stack Configuration

The previous work involving the system was performed on a plate-and-frame device consisting of one membrane separating a charge compartment from a vacuum compartment as shown in Figure 2. Although it was satisfactory for carrying out membrane comparison studies and process variable studies, its bulky construction renders it unsuitable for scale-up operations. On the other hand, a stack configuration has the advantage of being compact and flexible.

A permeation cell is formed by stacking together pieces of plastic cut-outs, titanium sheets and a titanium frame as shown in Figure 3. The permeation cells are, in turn, stacked together to form a VDR stack. The capacity of the stack is readily changed by removing or adding permeation cells to the stack. The flow characteristics of the various streams are varied by using plastic cut-outs of different thickness and design.

The stack configuration was also chosen because of its similarity with the plate-and-frame device and because Ionics has wide experience with such a design. Similarity with the plate-and-frame device allows a smooth and quick conversion to the stack design and maintains the relevance of previous data.

The first stack constructed is shown in Figure 4. The wastewater charge is introduced into the stack at ambient temperature using a magnetic drive pump. It enters the inlet part of the stack and flows along the plastic cut-outs and returns to the charge reservoir for continuous recirculation until waste treatment is completed. Heated water from a constant temperature bath, maintained at 348°K (165°F) is recirculated through the stack in the same way.

Within the stack heat transfer occurs from the heating fluid compartment through conductive titanium sheets to the adjacent charge compartment. Direct heating of the wastewater with an electric heater is

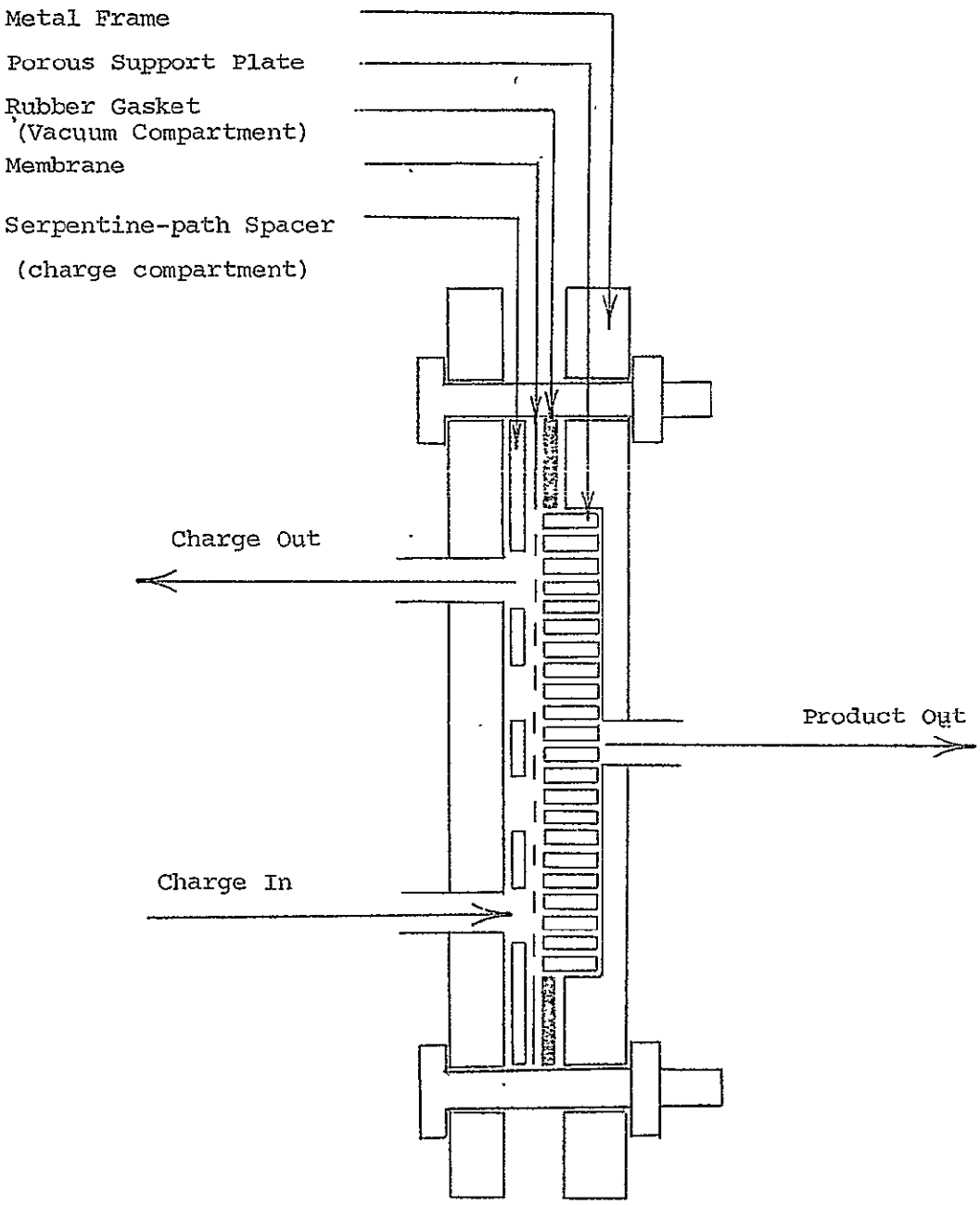


Figure 2. THE PLATE-AND-FRAME CELL

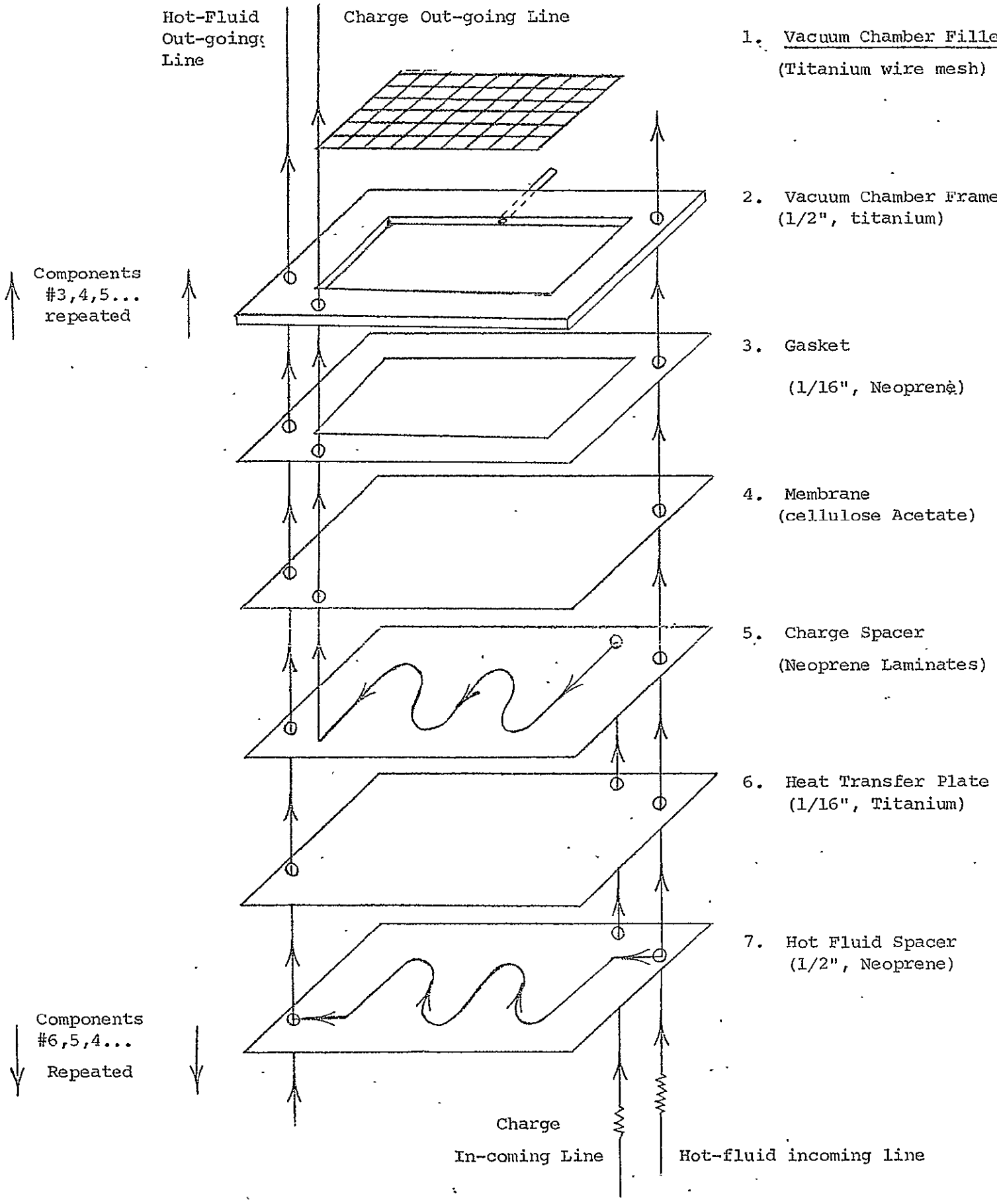


Figure 3. EXPLODED VIEW OF THE VAPOR DIFFUSION STACK

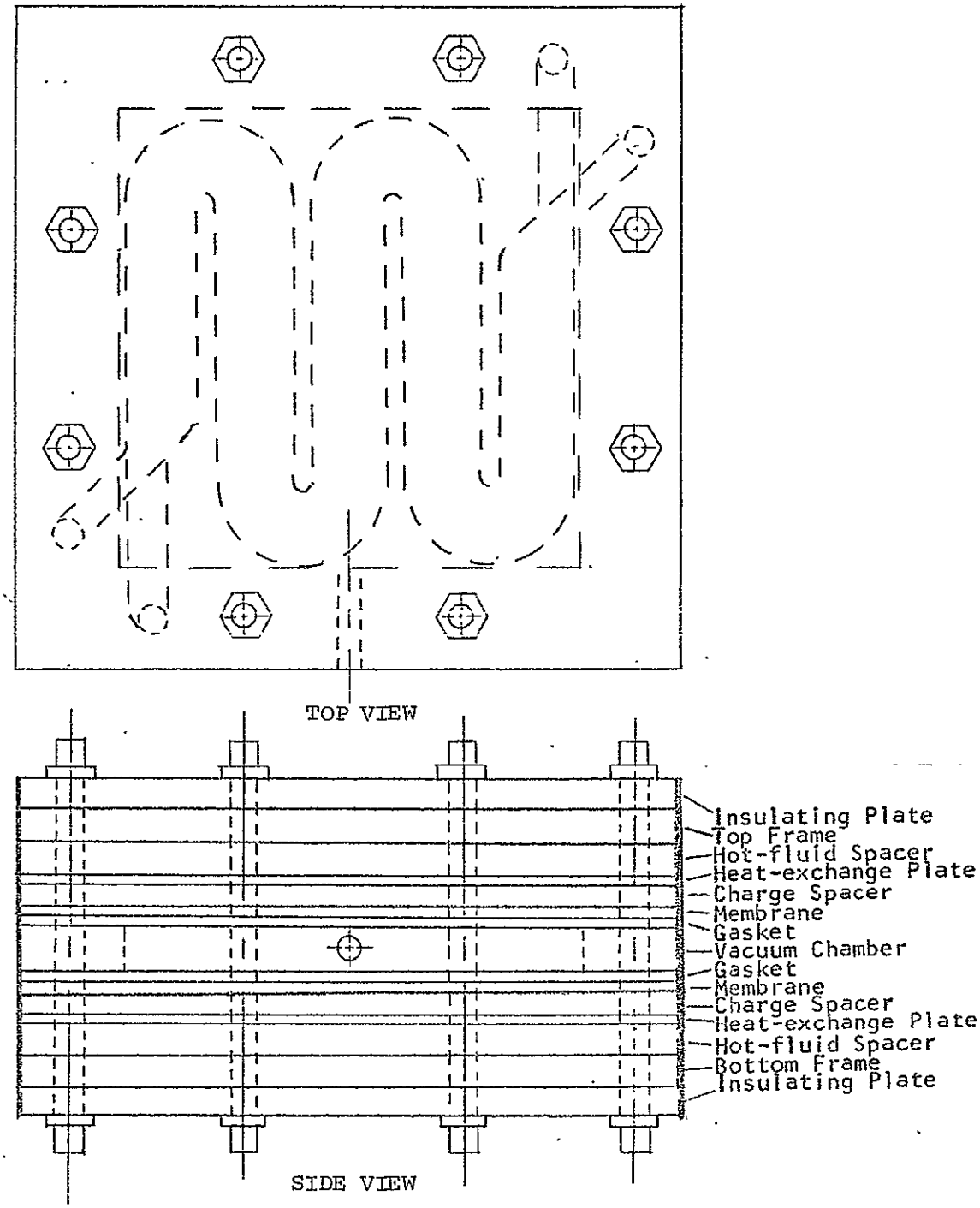


Figure 4. Diagram Illustrating the 2-Membrane Stack

avoided for several reasons. Local heating may cause the generation of gaseous material due to urea decomposition and local boiling. These gases may interfere with system operation. Indirect heating takes place over a larger surface area and hence requires a lower temperature. At the same time indirect heating allows for easy adaptation to on-board cooling loop from fuel cells, payloads and other spacecraft systems. Such an adaption will conserve the usage of valuable on-board electric power while providing supplemental spacecraft cooling. It is especially useful during missions of high payload deployment and as a back-up cooling unit.

The charge constituents first dissolve into the membrane selectively depending on the molecular size, shape and chemical properties of the particular charge constituents. At low charge velocities, this process is severely affected by the boundary layer resistance to mass transfer. At high charge velocities characterized by turbulent flow, the rate determining step is the diffusion of the vapor through the membrane.

The heated wastewater evaporates through the membrane phase separator and is removed from the stack by a vacuum pump. A cold-water condenser is used to condense the vapors in order to monitor the permeation rate and the condensate quality. In an on-board unit both the vacuum pump and the condenser-collector components will be omitted. The permeated vapor is simply vented, through a series of safety and control valves, to space vacuum.

A five day continuous run was carried out. As shown in Figure 5, the water flux behaves in a similar manner to the corresponding flux in a plate-and-frame device. Several problems were encountered during this initial test run, such as the leakage of the charge out of the stack and into the vacuum compartments. External leakage is prevented by the uniform clamping pressure on the stack. This is achieved by

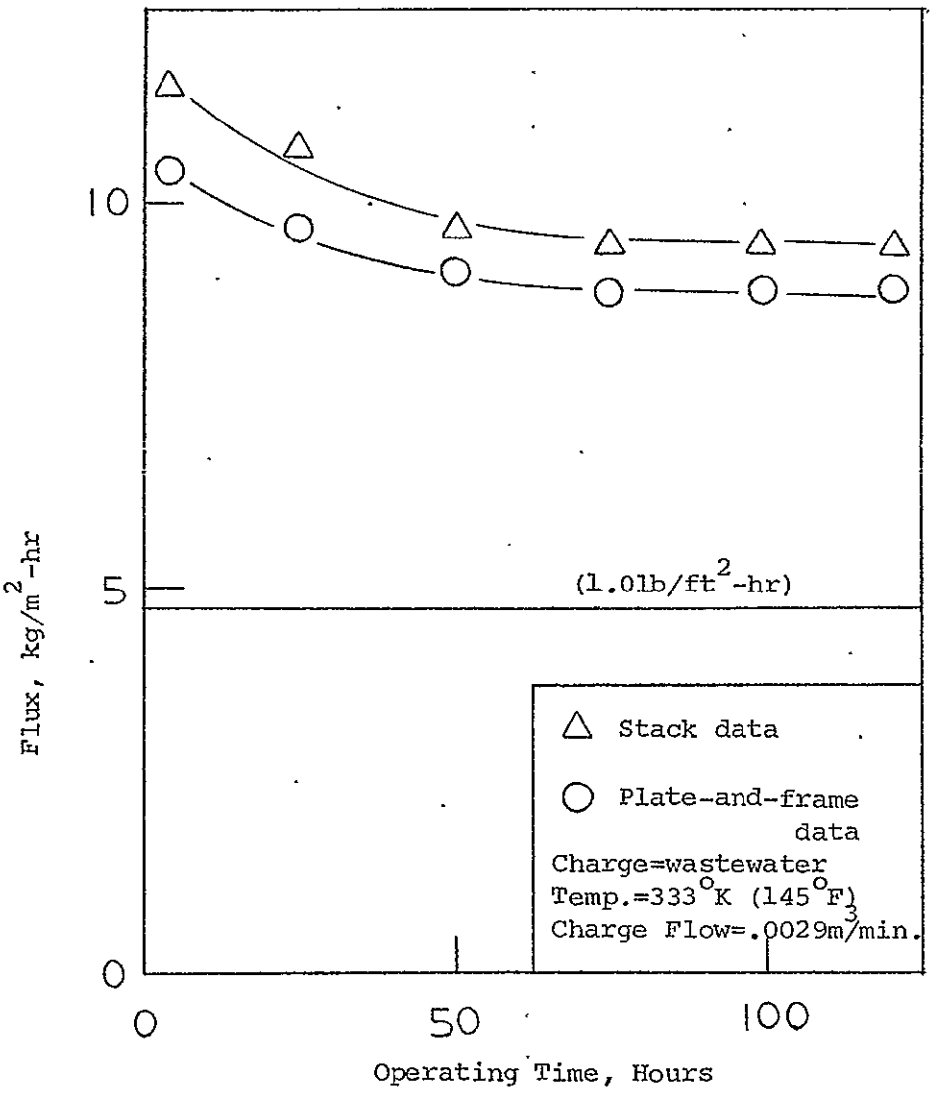


Figure 5. WATER FLUX AS A FUNCTION OF OPERATING TIME

tightening the nut and bolt assemblies with a constant torque following a predetermined sequence.

Internal leakage to the vacuum compartments occurs around the inlet and outlet region of the charge compartments at the membrane-gasket interface. Sealing requires minor design changes involving metal inserts to support the membrane. Although a complete seal was eventually achieved, this region requires further studies because system failure is probably most likely to occur here.

The required size of a VDR stack to meet the waste treatment associated with a four-man crew is a 4-cell stack. Based on a combined wastewater of 3.3kg (7.3 lbs) per man-day, and 90% water removal, the total amount of daily waste rejection is 11.9kg (26.1 lb). Assuming a conservative estimated average flux of 4.0kg/m^2-hr, (0.80 lb/hr-ft^2) and an average operating day of 18 hours, the total membrane area required to reject the daily waste is 0.169m^2 (1.62ft^2). A four-cell stack has an effective membrane area of 0.176m^2 (1.91ft^2) or 16% in excess of the treatment requirement. Such a four-cell stack was next constructed.

Figure 6 shows the components of the stack and the flow schemes of the charge and heating-fluid loops. Figure 7 is a schematic diagram of the entire test system. A preliminary test was carried out. Flux data collected behaved similarly to the corresponding data obtained from the one-cell stack. A complete seal was achieved using similar techniques. A higher capacity charge pump was obtained for the four-cell stack.

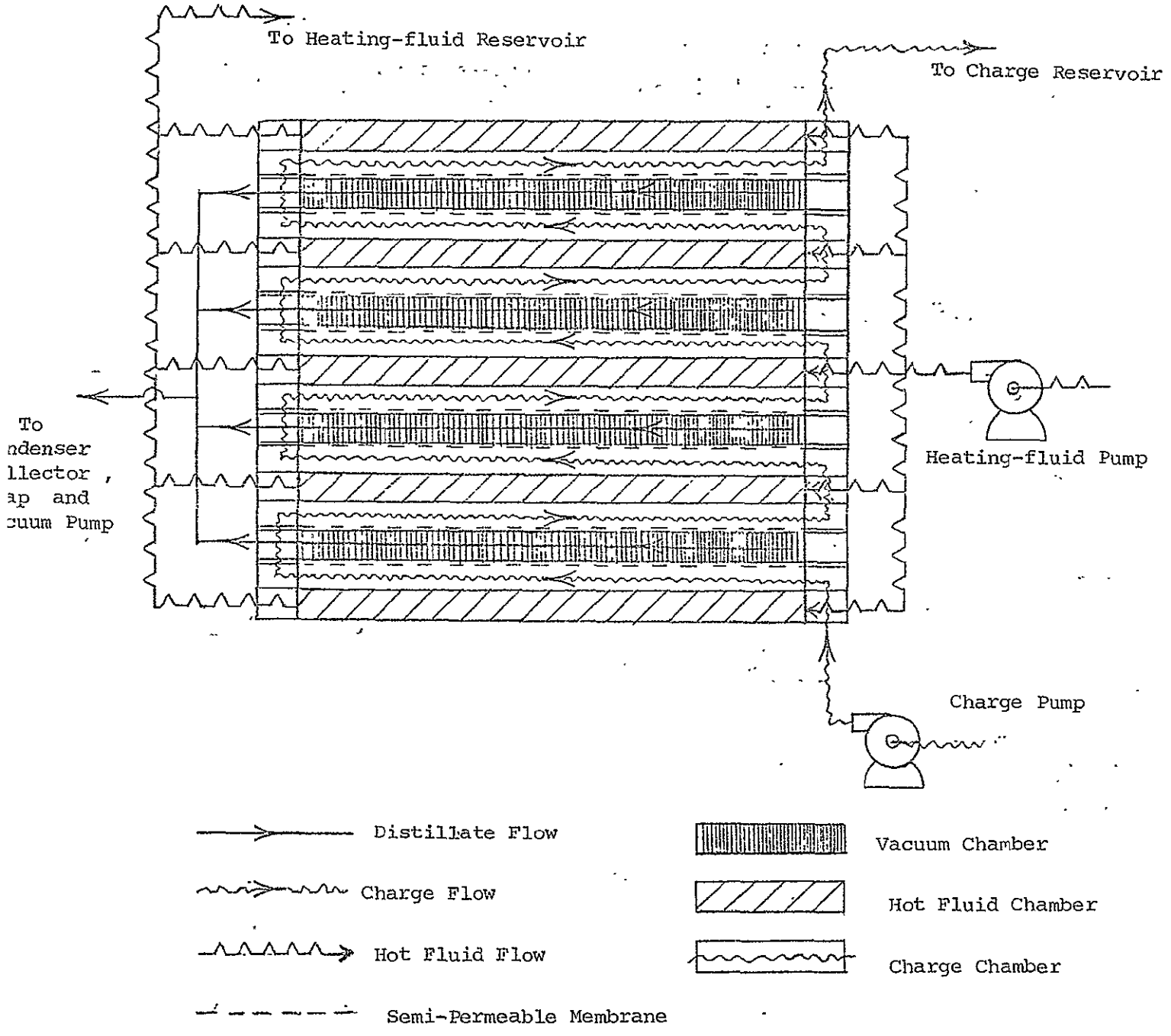
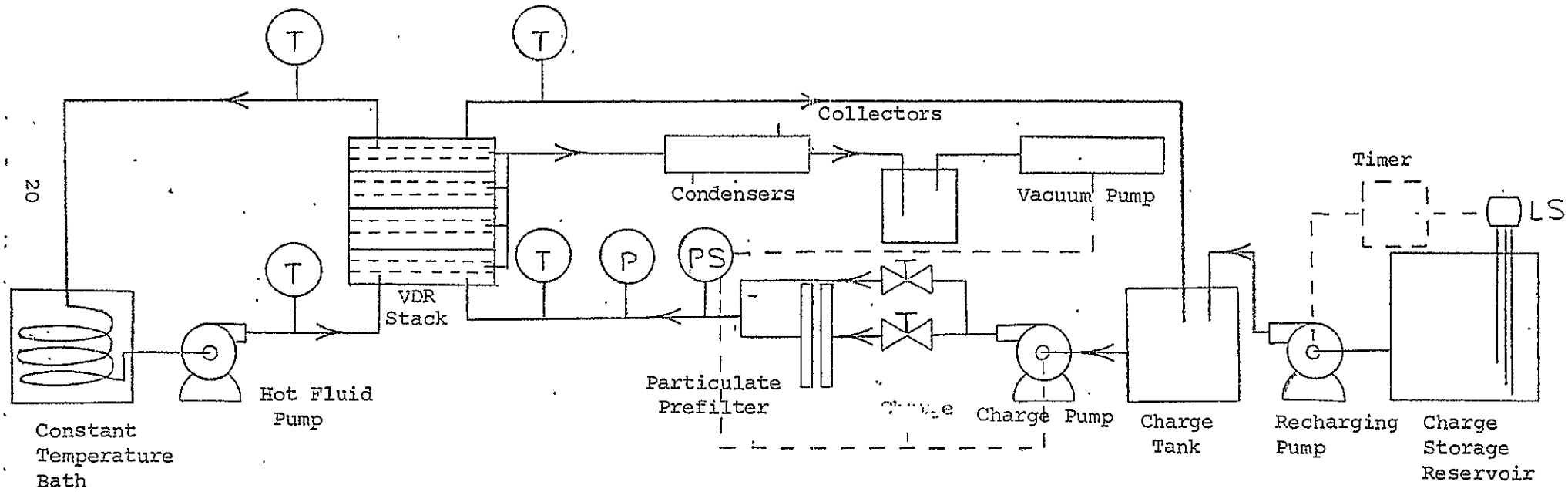


Figure 6. ILLUSTRATION OF THE COMPONENTS AND FLOW PATTERN WITHIN THE STACK



T = Temperature Indicator
P = Pressure Indicator
PS = Pressure Switch
LS = Level Switch
--------Electrical connections

Figure 7. SCHEMATIC DIAGRAM OF THE TEST SYSTEM

Task 2 Water Flux Studies

A. The Charge/Evaporator Temperature

The driving force within the VD-WR system is the water vapor pressure gradient established by the evaporator and condenser temperature difference. The higher vapor pressure region is described by the evaporator characteristics -- the charge temperature, the charge flow-rate and the charge composition. The lower vapor pressure region is described by the condenser temperature.

Water flux is particularly sensitive to the charge or evaporator temperature. Various investigators have shown that the relationship is of the Arrhenius type, i.e. the natural logarithm of water flux varies inversely as the absolute temperature of the evaporator. Figure 8 shows this relationship based on actual data. Temperature is also an important operating parameter in that it can be readily controlled to vary the rate of over-board venting and on-board cooling.

Increasing the evaporator temperature leads to a significant increase in water flux and an increase in the cooling capacity of the unit. A high flux means a decrease in the requirement for membrane surface area, and, hence, a decrease in system weight and volume penalties. High evaporator temperature is also desirable for pasteurization purposes.

The original HSD unit called for lowering of the evaporator temperature and chemical pretreatment of the urine charge to deter urea decomposition into ammonia. The decomposition might interfere with the process. Earlier work performed under this contract and the related contract by Gulf South Research Institute showed that urea decomposition in the absence of pretreatment at high temperatures was not severe because of the buffering action of urine components and the inactivation of the enzyme urease.

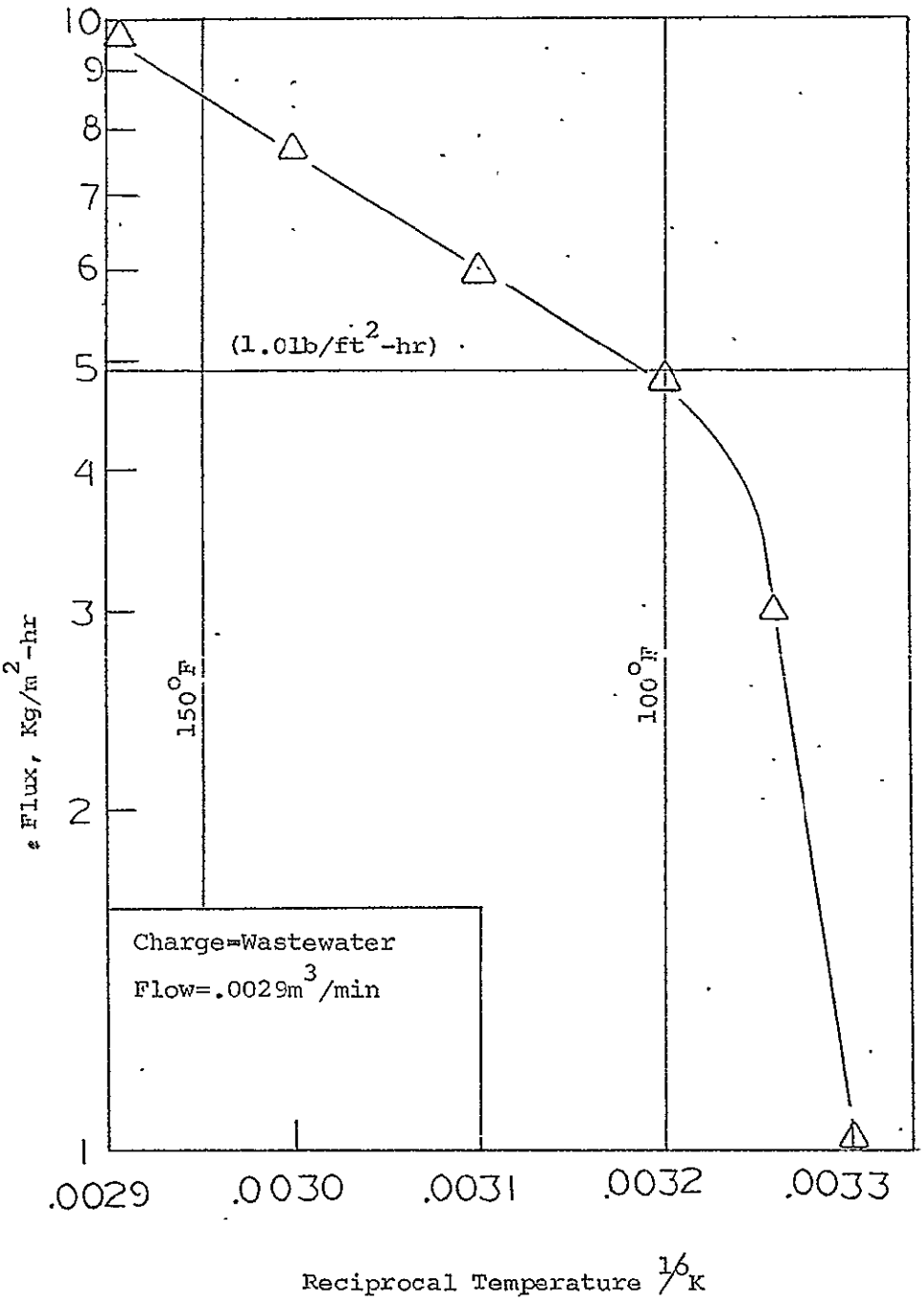


Figure 8. FLUX AS A FUNCTION OF TEMPERATURE

The maximum temperature for the evaporator is probably restricted by the temperature level of accessible on-board heat source. It is expected that the Freon cooling loop from the fuel cells can provide sufficient heat at a temperature of 333-347°K (145-165°F). An efficient heat exchange component can probably maintain the evaporator temperature in the 331-341°K (140-155°F) range for VDR application.

In-stack heat-exchange between the heating-fluid and the charge depends on the minimization of the major resistance to heat transfer which lies in the fluid films, the relatively stagnant boundary layers formed at both surfaces of the conductive metal plate. Turbulent flow within the charge compartment is required to minimize the effects of concentration polarization at the charge-membrane interface. Turbulent flow within the heating fluid compartments needed investigation. Experiments showed that a heating-fluid velocity of 0.25m/sec (0.83ft/sec) corresponding to a Reynolds Number of 2050 was sufficient to maintain an evaporator temperature of 331-341°K (140-155°F). This assumed that water was the heating-fluid and flat titanium plates were used as the conductive media, and that the on-board heat source was at a temperature of 333-347°K (145-165°F) and of sufficient flow. The actual heating capacity of the on-board heat source is not known at this time. It is desirable to incorporate an electric heater into the system to provide additional heat energy when required so that the performance of the VDR is not completely dependent on the heat source.

B. Charge Flow Rate

In any selective mass transfer system a boundary layer effect exists at the liquid-membrane interface. This layer has a disproportionately high concentration of low-permeability constituents and is relatively stagnant. It represents resistance to mass transfer from the bulk solution to the membrane. The thickness of the boundary layer can be decreased by promoting turbulent flow at the interface.

The plot of water flux as a function of charge velocity is shown in Figure 9. Flux varies as the 0.42 power of the velocity up to a velocity of 0.18m/sec (0.60ft/sec) beyond which increments in velocity lead to progressively smaller increments in flux. Above a velocity of 0.30m/sec (.99ft/sec) any increase in charge velocity has negligible effect on water flux. A charge velocity of 0.30m/sec (.99ft/sec) was selected as the desired charge velocity.

It was experimentally determined that water flux is also a function of the thickness of the charge spacer and the spacer design. A decrease in spacer thickness leads to an increase in pressure drop. A few spacer designs were investigated. Mixing appears to be maximum using a design as shown in Figure 10. This is based on the observation of flux behavior as well as the deposition of precipitate on the membrane surface as charge velocity is decreased. The final selection is a three-ply laminate with bridges on every ply to enhance mixing. The bridges on each ply are off-set so as to permit flow through the spacer. With this particular spacer design and a charge velocity of 0.30m/sec (.99ft/sec) the desired flux was obtained. A plot of water flux as a function of charge flow using this new spacer design is shown in Figure 11.

C. Membrane Selection

The driving force in the VD-WR system is the water vapor pressure gradient established between the hot evaporator and the cold condenser. Diffusion through the gap is impeded by the presence of noncondensables and the boundary layer. Occasional purging of noncondensables and the creation of forced convection (natural convection being impossible under zero-gravity environment) are essential to avoid flux decay. The use of a vacuum pump (or space vacuum) as a mechanical means of vapor removal is very effective in that the impedance to diffusion is practically eliminated. At high vacuum, low vapor pressure charge constituents that permeate the

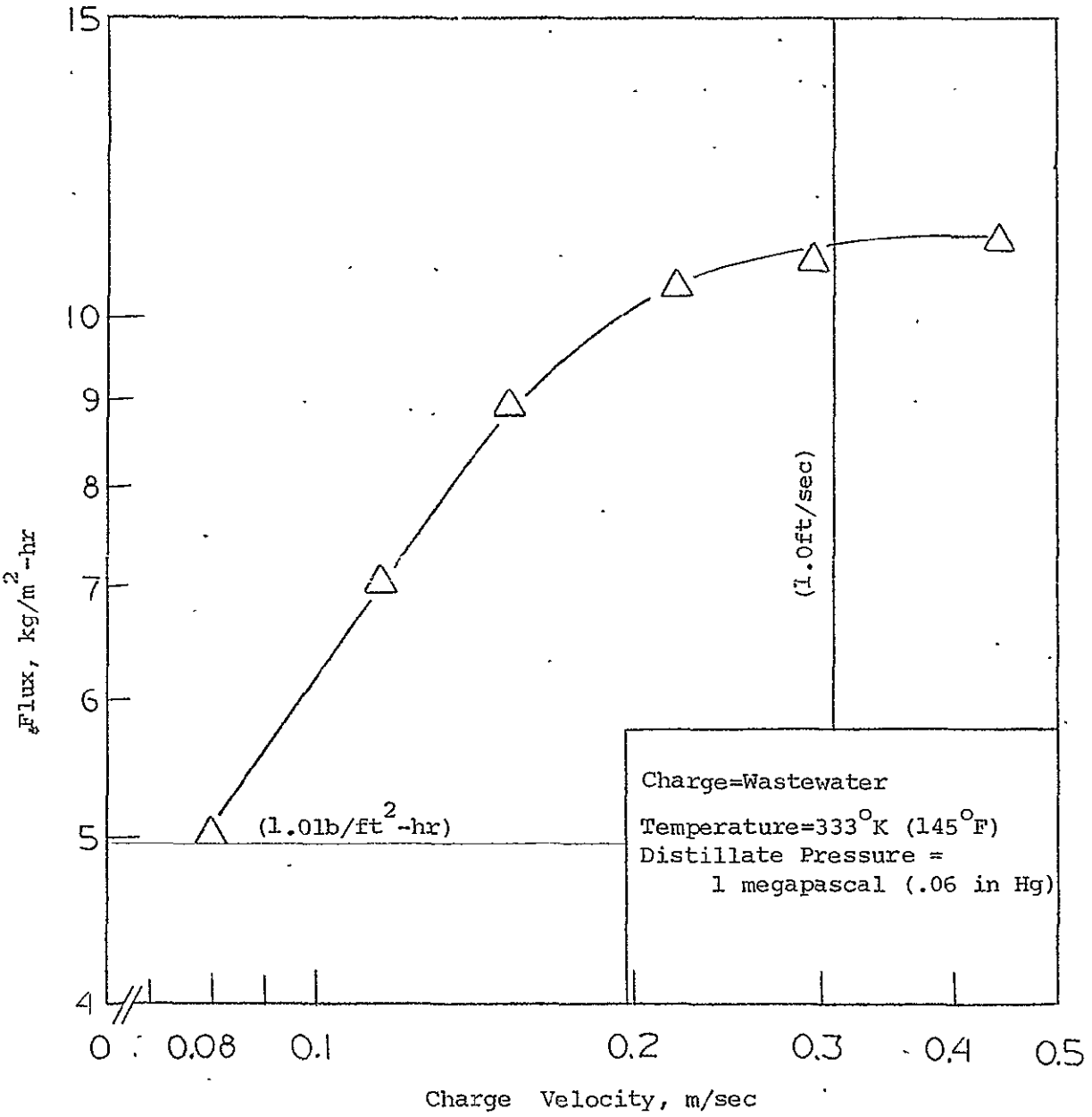


Figure 9. FLUX AS A FUNCTION OF CHARGE VELOCITY

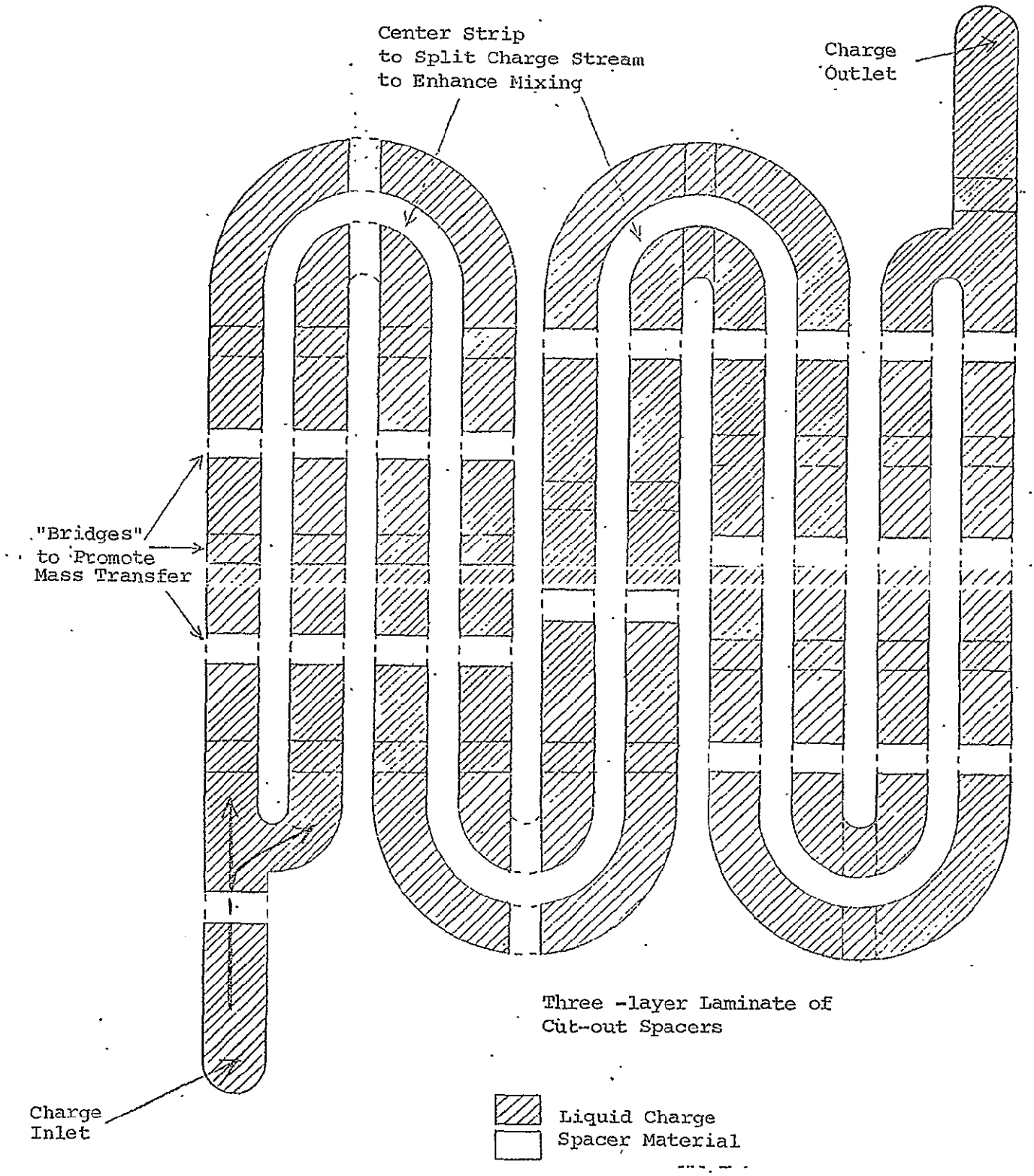


Figure10. TOP VIEW OF CHARGE SPACER ILLUSTRATING CHARGE FLOW PATTERN

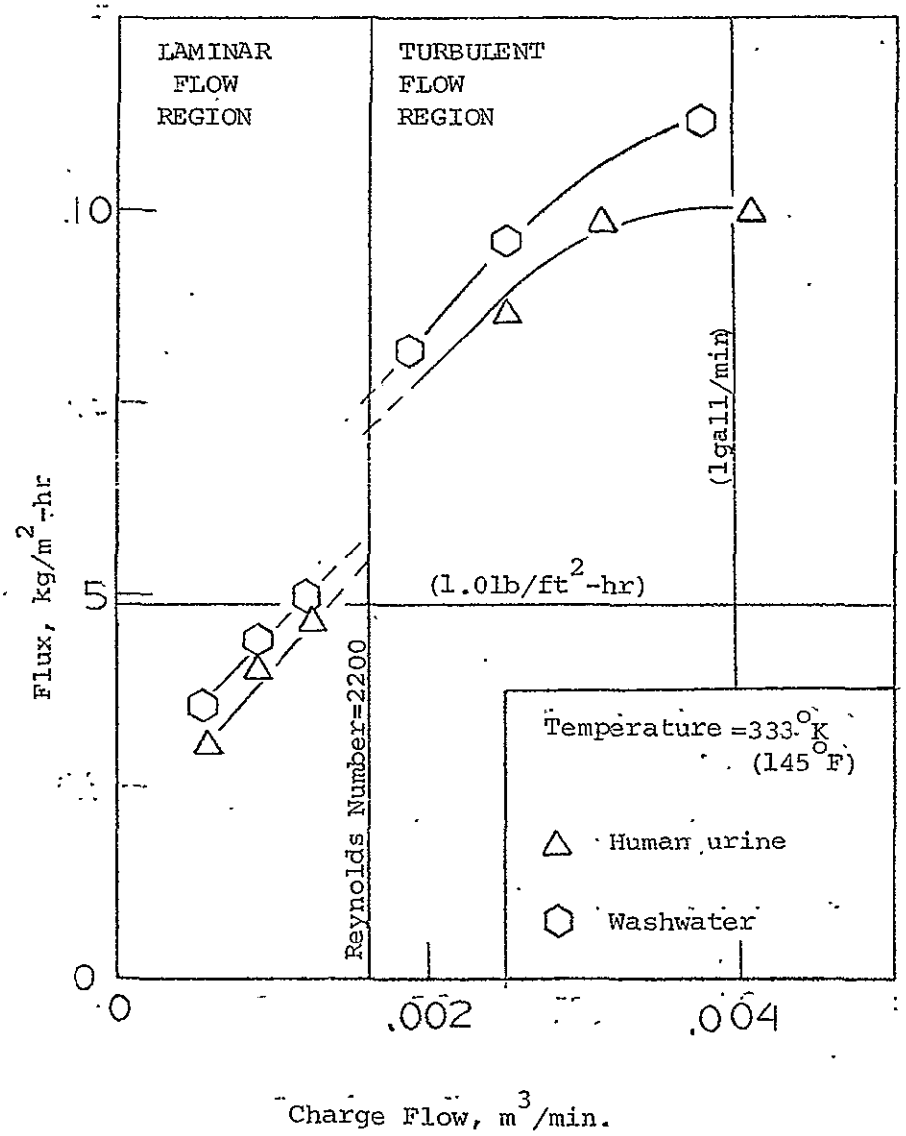


Figure 11. FLUX AS A FUNCTION OF CHARGE FLOW RATE

membrane are immediately evaporated. The major resistance to mass transfer appears to be the charge-membrane interface. (See previous section on the variation of water flux with charge flow rate). At high charge flow rates, this boundary layer is minimized and the vapor diffusion through the membrane becomes the rate determining factor. This diffusion rate is a function of charge temperature and composition and is characteristic of a particular membrane. Since the charge composition is an independent variable and the charge temperature is defined by the temperature of the on-board heat source, the selection of the membrane phase-separator is a very important task.

Ideally, the membrane should be highly permeable to water vapor and nonpermeable to wastewater solutes. It should have a minimum thickness and yet high strength and integrity to minimize the possibility of membrane rupture.

Several membrane selection studies have been conducted by various investigators over the years. The results from the early work performed under NAS2-7651 showed that many commercially available membranes for reverse osmosis application perform satisfactorily in terms of water flux and selectivity.

The best candidate is a cellulose acetate asymmetric membrane commercially produced by Envirogenics System Company of El Monte, California for reverse osmosis application. This membrane is also available cast on a polypropylene cloth to improve membrane strength and integrity. This membrane is recommended for application in the system. It has withstood several extended tests satisfactorily. The major problem associated with this membrane is its requirement of wet storage.

D. Distillate Pressure

The impedance to vapor diffusion can be eliminated by using a vacuum

pump (or space vacuum) to mechanically remove permeated vapors. However, ultra high vacuum (such as space vacuum) will cause instantaneous evaporation and freezing of the water vapor. This may physically plug up valves and pipes. As such, it is desirable to control the rate of over-board venting.

The effects of operating vacuum on the water flux of the VDR warrant investigation. An experiment was conducted to study this. Figure 12 is a plot of water flux as a function of distillate absolute pressure. The latter was controlled by bleeding air through a needle valve at different rates. As noted from the plot, over the range of 2-13.5 megapascal (0.58-4.2 inches of mercury) the impedance to vapor diffusion is eliminated and the vapor diffusion through the gap is not the rate determining factor, confirming previous observations.

Above 13.5 megapascals (4.2 inch Hg) the water flux drops rapidly with increasing distillate pressure because of the accompanying increase in impedance to diffusion. At an absolute pressure of 21.3 megapascals (6.4 in Hg) the flux is negligible. The total impedance to diffusion becomes the controlling factor.

The range that is most applicable to the VD-HR because of the ultra high vacuum of outer space is the 0-2 megapascal range shown in the Figure. Although ultra high vacuum is not achievable by means of the vacuum pump, it can be noted that within this small pressure range, flux increases with decreasing pressure (increasing vacuum). The actual flux in ultra high vacuum is, therefore, not known, neither is the extent of any adverse effects.

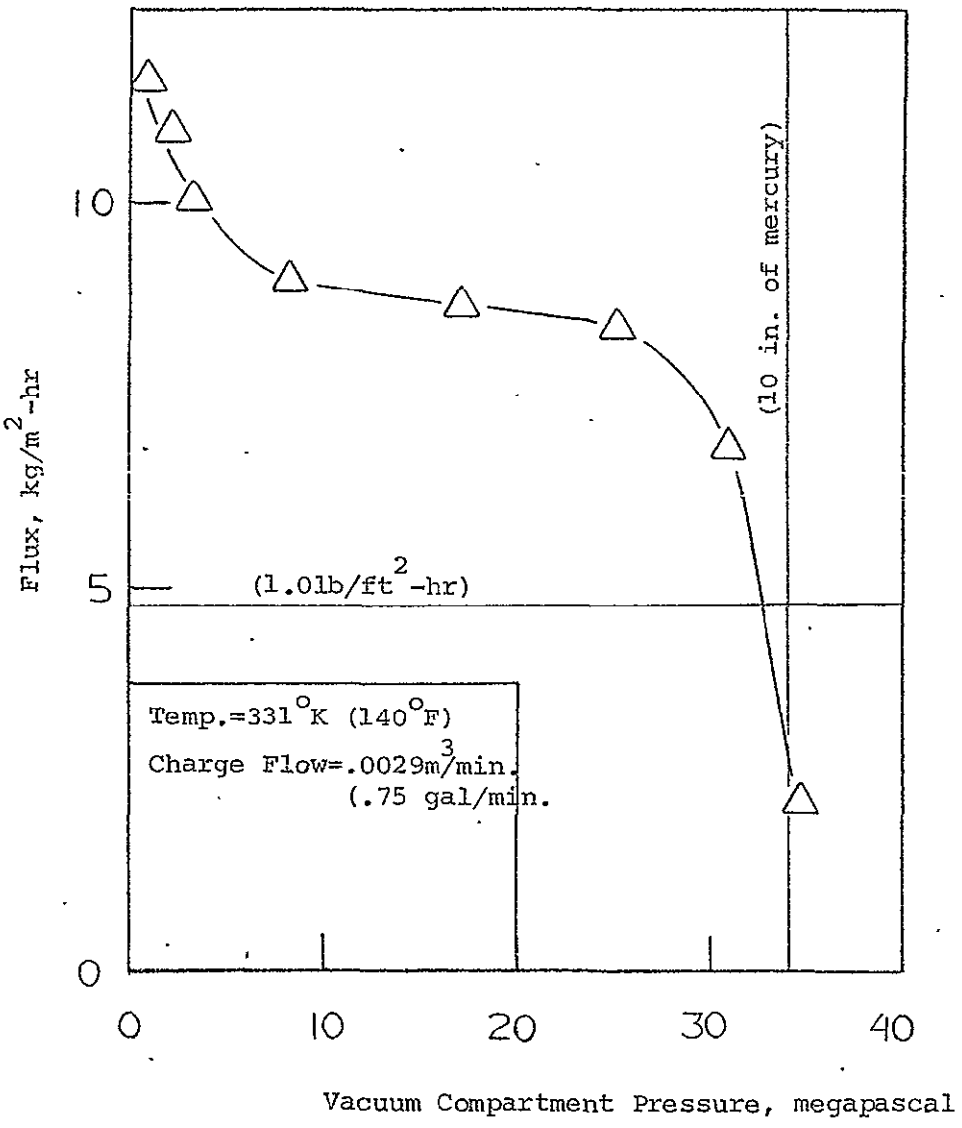


Figure 12. FLUX AS A FUNCTION OF VACUUM COMPARTMENT PRESSURE

Task 3 Distillate Quality Studies

Although the permeated water need not meet potability standards for VD-HR application, it was desirable to monitor the quality of the distillate for several reasons. Permeated solutes may plug up the membrane surface, and the piping and valves that connect the vacuum compartments to space vacuum. The permeated solutes may interfere with spacecraft instruments and experiments. It may become necessary to recover a portion of the permeated water for reuse if the on-board water supply from the fuel cells becomes inadequate for astronaut usage.

During the various tests the permeated condensables were routinely collected to monitor product water quality. It is noted that the highly volatile constituents were collected in the condensate only to the extent of their solubility in water at the condensate temperature. Some volatile noncondensables were lost in the vacuum pump trap and were not recovered for assay purposes because of the difficulty in the entrapment and recovery of these constituents. Furthermore, they are mostly volatile organics and the spacecraft baseline systems, such as the feces inactivation unit, already vent volatile organics and their interference with instruments and experiments is expected to be negligible.

Table I shows the typical range of the contaminants present in the condensate samples and compares them to the potability standard of the United States Public Health Service. Post-treatment with activated charcoal and ion exchange resin will be needed to remove the residual organics and ammonia respectively, if it becomes necessary to recover the water to meet the astronauts requirements. In the case of overboard venting, the residual materials may interfere with spacecraft equipment and experiments or they may plug up the piping and valves connecting the system to space vacuum. However, these are outside the scope of the present program.

TABLE I: COMPARISON OF PRODUCT WATER CONTAMINATION

WITH ESTABLISHED POTABILITY STANDARDS

(The samples have not been post-treated with charcoal or ion-exchange resin.)

Cotaminants	Sample (mg/ℓ)	SSD-NAS Limits (mg/ℓ)	USPHS Limits (mg/ℓ)	WHO Limits (mg/ℓ)
Total Solids	250-300	1000	500	500
Total Nitrogen	80-130	NS	NS	NS
Ammonia Nitrogen	60-90	NS	NS	NS
C. O. D.	150-250	200	NS	NS
pH	8-9.5	NS	6.5-8.5	7-8.5
LAS	5-10	NS	NS	NS
Sodium	10-30	200	200	NS
Potassium	5-10	100	100	NS
Calcium	5-15	NS	NS	75
Magnesium	5-15	150	120	50
Zinc	0	NS	5	5
Iron	0	NS	0.3	0.3
Copper	0	3.0	1.0	1.0
Chloride	20-40	450	250	200
Sulfate	5-10	250	250	200
Phosphate	5-10	150	100	NS
Turbidity	7*	NS	1*	5*
Odor	Strong, Obnoxious	NS	3*	NS

*Turbidity units

Task 4 Membrane Life Studies

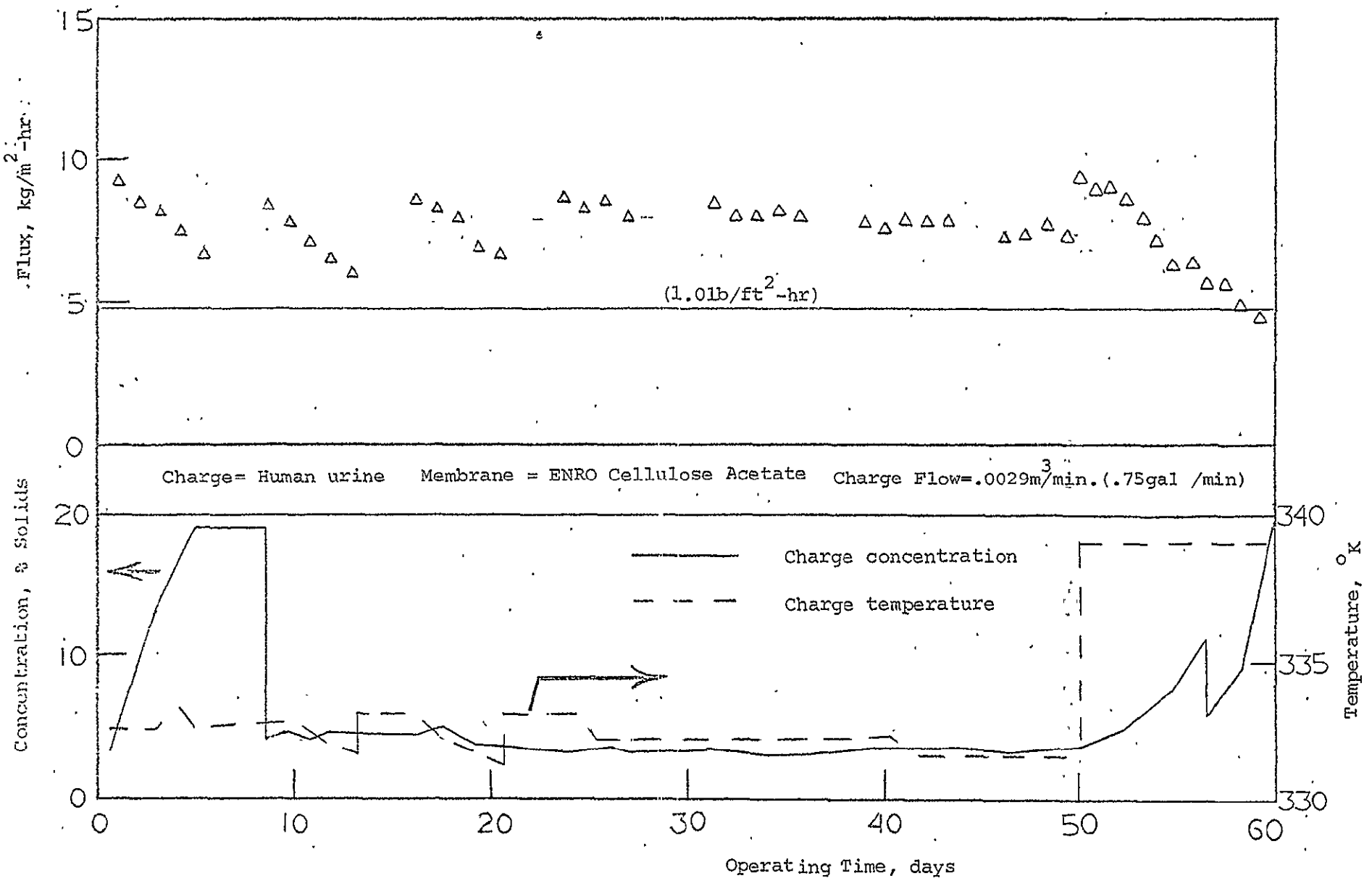
The life and structural integrity of the membrane phase-separator is a most crucial factor in any VD-WR process. Membrane failure represents a most important mode of system failure, in terms of its seriousness and its likelihood of occurrence. It usually causes interruption of the whole process and may call for actual repair work.

Several prolonged tests have been conducted to investigate the modes of membrane failure. Although the cellulose acetate membrane is susceptible to hydrolysis and rupture under extreme conditions, such failure was not observed. In these tests, the membrane was subjected to widely varied operating conditions that are not expected to occur in normal VD-HR application, such as, abrupt changes in charge composition and temperatures and repeated switching of the charge pump and vacuum pump from an "off" positon to a "high"position.

However, membrane fouling was usually observed. Previous data has indicated that the accompanying flux decline was more severe at elevated temperatures, high solute concentrations, and low charge velocities for a given membrane; and was more severe for highly hydrophilic membranes. More significantly, the rate of flux decline was observed to decrease with operation time -- membrane became stabilized after the initial hundred hours.

Figure 13 summarizes a 60-day continuous test performed under the contract. The top section of the graph shows the water flux and the bottom section shows the changes in some of the operating conditions, namely, the charge concentration and the charge temperature. The charge velocity, pH level and the distillate pressure were also deliberately altered from time to time. The purpose for this variation in operating

Figure 13. . DATA FROM MEMBRANE LIFE STUDIES



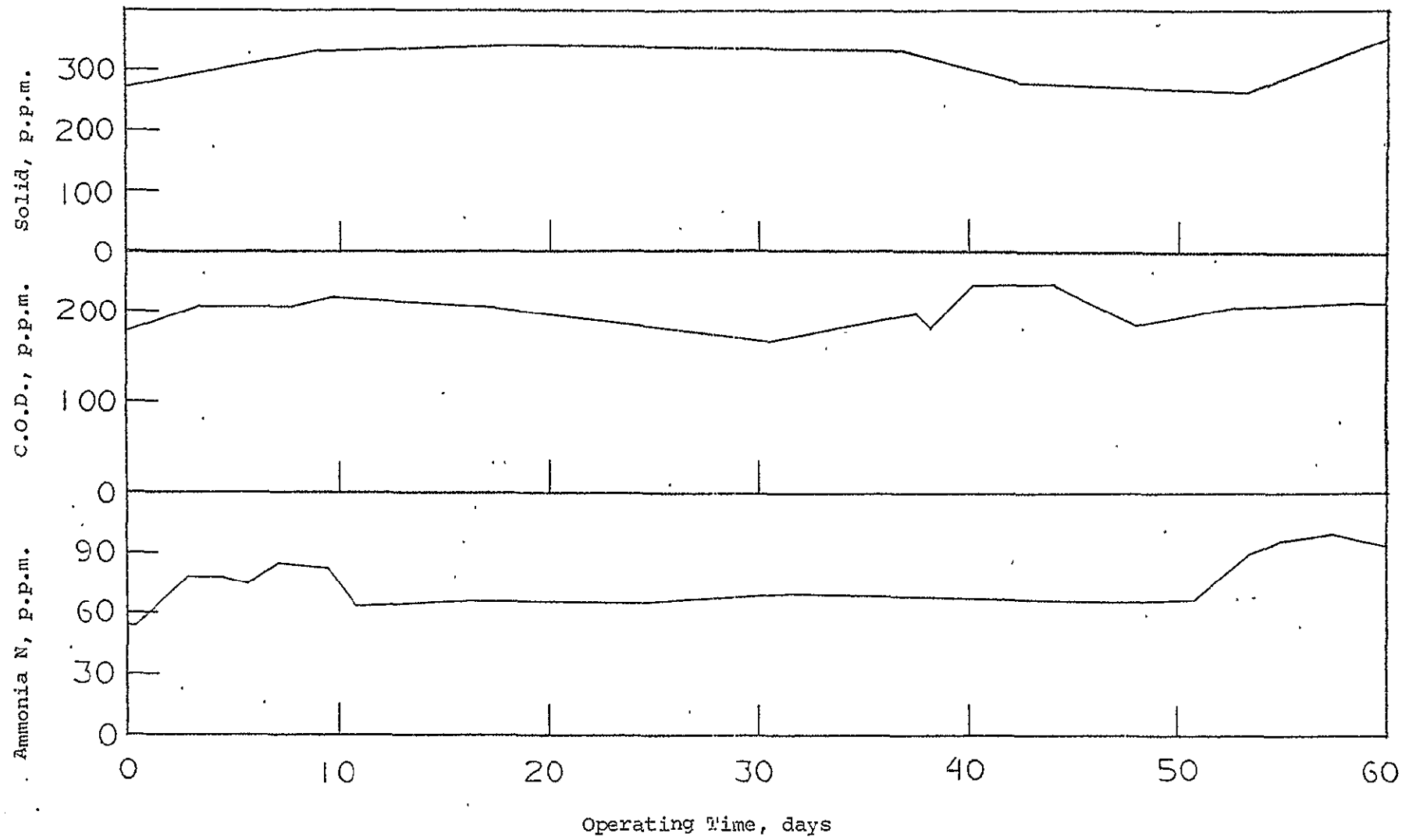
conditions is two fold -- to obtain additional flux data as a function of the particular independent variable and to subject the membrane to unusually strenuous operating conditions. No membrane rupture was observed throughout the test.

Figure 14 shows the product quality in terms of total residue, total chemical oxidation demand, and total ammonia nitrogen under the same operating conditions. As can be noted from Figures 13 and 14, the flux and product quality became stabilized after the initial decline. All data in this report is based on such a stabilized flux.

The same membranes were used in subsequent tests including another 20-day continuous run. The same stability in water flux and product quality was observed.

Figure 14. DISTILLATE QUALITY FROM MEMBRANE LIFE STUDIES

(See Figure 13 for Operating Conditions)



Task 5 Additional Studies

A. Soap/Detergent Studies

Although the comparison study of soaps and detergents was not included in the original program plan, the need arose during the course of using the soap recommended by NASA, namely Olive Leaf of Palmetto as manufactured by Rochester Germicide Corp. During testing using a combined urine-washwater charge, severe flux decay was observed. At the same time, the turbidity of the charge and the condensate also increased. Further investigation showed that the soap became hydrolyzed leaving a dark yellow oily slime on the membrane surface and a white precipitate in the wastewater charge. It was confirmed later that the soap became destabilized at the 330-341^{o}K (140-155^{o}F) temperature range at pH levels below 6.5. The precipitate and slime formation occurred only at charge solute weight fraction exceeding 0.20. Since this condition is unavoidable, in Vapor Diffussion operation, a different soap is needed.

A total of 18 different liquid soaps and detergents were obtained from their respective manufacturers. Their properties are shown in Table II. In addition, their stability in the presence of concentrated wastewater (0.25 solute weight fraction) was examined by refluxing the soap-wastewater mixture at 330-341^{o}K (140-155^{o}F) for a period of 48 hours. Since these were all commercial hand soaps, their compatibility with the human skin was assumed.

Out of the 18 soaps and detergents, two candidates were selected as the most stable ones and tested in a five-day continuous run in the test unit. No excessive foaming, precipitation, clouding of the condensate or any other adverse effect was noted at any time. A subsequent sixty-day continuous test using one of these detergents, the Sulframin 1260 Slurry by Witco Chemical Corporation, confirms the suitability of the detergent for VDR application. The main ingredient of this formulation is sodium dodecyl benzene

Table II. Soaps/Detergent Studies

Name	Manufacturer	Active Surfactants % Solids	Type	ADDITIVES Emollient	Perfume	Dye	pH	Stability*
1. Palmetto	Rochester Germ. Co.	20	K, coconut oils	yes	yes	yes	10.0	P,H
2. Royal Crest	Rochester Germ. Co.	20	K, coconut oils	yes	yes	yes	9.9	P,H
3. Miranol JEM	Miranol Chem. Co.		Amphoteric	no	no	yes	10.3	S
4. Opal Lemon 540	Murphy-Phoenix Co.	15-40	K, coconut oils	yes	yes	yes	10.6	S
5. Coco-Castile	S & E Chem. Co.	15-40	K, coconut oils				9.2	P,H
6. Germa Medica	Huntington Labs, Inc.	40	K, vegetable oils	a lot	yes	yes	9.3	S
7. Liqua San C	Huntington Labs, Inc.	40	K, vegetable oils	little	yes	yes	9.4	N.T.
8. Blandite	Lester Labs, Inc.	30	Na, coconut oil	yes	yes	yes	9.0	E
9. Amazon 15	Trio Chem. Works, Inc.	15	Na, vegetable oil	yes	yes	yes	9.6	P
10. Coco-Castile RTU	Essential Chem. Corp.	15-40	K, coconut oil	yes	yes	yes	9.5	P
11. Ever Kleer	Essential Chem. Corp.	40	K, coconut oil	yes	yes		10.1	N.T.
12. Antiseptic	Essential Chem. Corp.	20	K, coconut oil	yes	yes	yes	9.8	N.T.
13. Miranol C2M	Miranol Chem. Corp.	40	Amphoteric	no	no	yes	8.2	S
14. Essanee	S & E Chem. Co.	15-40	N.K.	yes	yes	yes	8.2	E
15. Sulframin 1260	Witco Chem. Corp.	40	Na,dodecyl sulfonate	yes	no	yes	7.0	S
16. Basic H	Shaklee Products	15	N.K.	no	no	yes	6.0	S
17. Neutrafoam	S & E Chem. Co.	15-40	N.K.	yes	no	yes	6.8	P,H
18. Emulso	Emulso Corp.	18	Na, alkyl benzene sulfonate	yes	yes	yes	6.5	S

N.K. = not known, manufacturer would not disclose.

*Stability refers to the stability of a 1:5 dilution of the soap in water added to an equal amount of a 40% NaCl-10% urea solution. The solution is refluxed at 165°F for 48 hours. P=precipitation occurs; H=soap appears to hydrolyze into an oily material, usually fluffy in texture; S=stable, i.e. no change; E=emulsification appears to have occured-no solid formed, but an oil phase appears at the bottom; N.T.=not tested.

sulfonate which may be assayed by the methylene blue indophenol method for anionic surfactants.

The other candidate found suitable for VDR application is Miranol JEM, a product of Miranol Chemical Company of which the main constituent is an amphoteric imidazoline sulfonate.

B. Material Balance in the Unit

An experiment was designed to investigate the material balance in the unit. The main reason for performing this is that previous data showed that nonvolatile species such as sodium chloride and urea permeated the membranes. These species might build up on the vapor-side of the membrane and lower the overall flux or plug up the lines and valves on this side of the membrane. In actual experiments the performance of the VD-WR as a whole has never been seriously interrupted. However, on disassembling the unit, solutes were actually observed to have accumulated on the vapor-side of the membrane surface. It was concluded that a build-up of permeated nonvolatiles occurred initially; but the membrane soon reached steady state at a nonvolatile concentration below saturation at which back diffusion would transport nonvolatiles back to the charge. Thus the system was tested 50 days without serious interference, both in terms of flux and distillate quality.

The system was charged with a 12-liter batch of human urine. The volume and amounts of the various major components were measured. The charge subsystem was carefully enclosed to prevent any loss due to evaporation or spillage. The unit was run continuously and the distillate was collected in two 8-liter flasks and the volatiles were entrapped in a series of cold traps containing boric acid solution at below 25°F (maintained with a NaCl-ice mixture), the exact volume and concentration of the acid solution having been premeasured. After about 10-liters of the liquid had been removed from the charge, the system was shut off and

the amount and contents of the charge, distillate and the boric-acid-trap solution were all carefully measured and shown in Table III.

From Table III a few observations may be made:

(a) About 88% of the permeated water was condensed, i.e. the flux values reported in this and the previous report were lower than the actual by some 12%;

(b) Some 6% of the NaCl was probably entrapped in the membrane interstices, the vapor-side of the membrane surface, and/or the vacuum chamber fabric;

(c) Amount of urea in the charge had dropped by 16.5% partly due to entrapment as suggested in (b) and partly due to previously reported observation that some urea was converted to NH_4HCO_3 and $(NH_4)_2CO_3$ and is no longer detectable by the urea assay;

(d) Because of (c) a discrepancy in the level of ammonia nitrogen is noted. Although appreciable amounts of ammonia N permeated the membranes and were absorbed by the acid traps, some ammonia N was generated in the charge due to urea decomposition. There is, thus, an overall gain in the total ammonia N.

(e) Overall, about 8% of the total nonvolatiles permeated through the membrane most of which was entrapped as suggested in (b); and

(f) Volatiles also permeated through the membranes; and some of these are trapped by the boric acid solution, notably ammonia, the remainder being removed from the system by the vacuum pump.

TABLE III: MATERIAL BALANCE EXPERIMENT

	Initial	Final	% Change (loss)
1. Mass Balance (gm)			
Charge	12.20	1.93	
Distillate	0	8.14	
Acid-traps	1.00	1.57	
Total	13.20	11.64	(12.3)
2. NaCl Balance (gm)			
Charge	103.2	96.4	(6.59)
Distillate	0	0.49	-
Acid traps	0	0	
Total	103.2	96.89	(6.06)
3. Urea Balance (gm)			
Charge	234.6	196.0	(16.5)
Distillate	0	1.08	-
Acid traps	0	0.08	-
Total	234.6	197.16	(15.9)
4. Ammonia N (gm)			
Charge	17.8	15.3	(14.0)
Distillate	0	0.72	
Acid traps	0	4.84	
Total	17.8	20.86	+ 17.2
5. Total Nonvolatiles (gm)			
Charge	398.3	365.8	(8.16)
Distillate	0	2.14	
Acid traps	0	17.3	
Total	398.3	375.24	(5.79)

Task 6 Fabrication and Testing of the Skid-Mount Unit

In the course of contract #NAS2-7651 several improvements were made on the HSD unit. In addition, VD-HR concept is a significant departure from the basic VD-WR unit built by HSD. In order to allow further tests to be conducted in this area outside of Ionics, Incorporated, a skid-mount unit was designed and fabricated as shown in Figure 15.

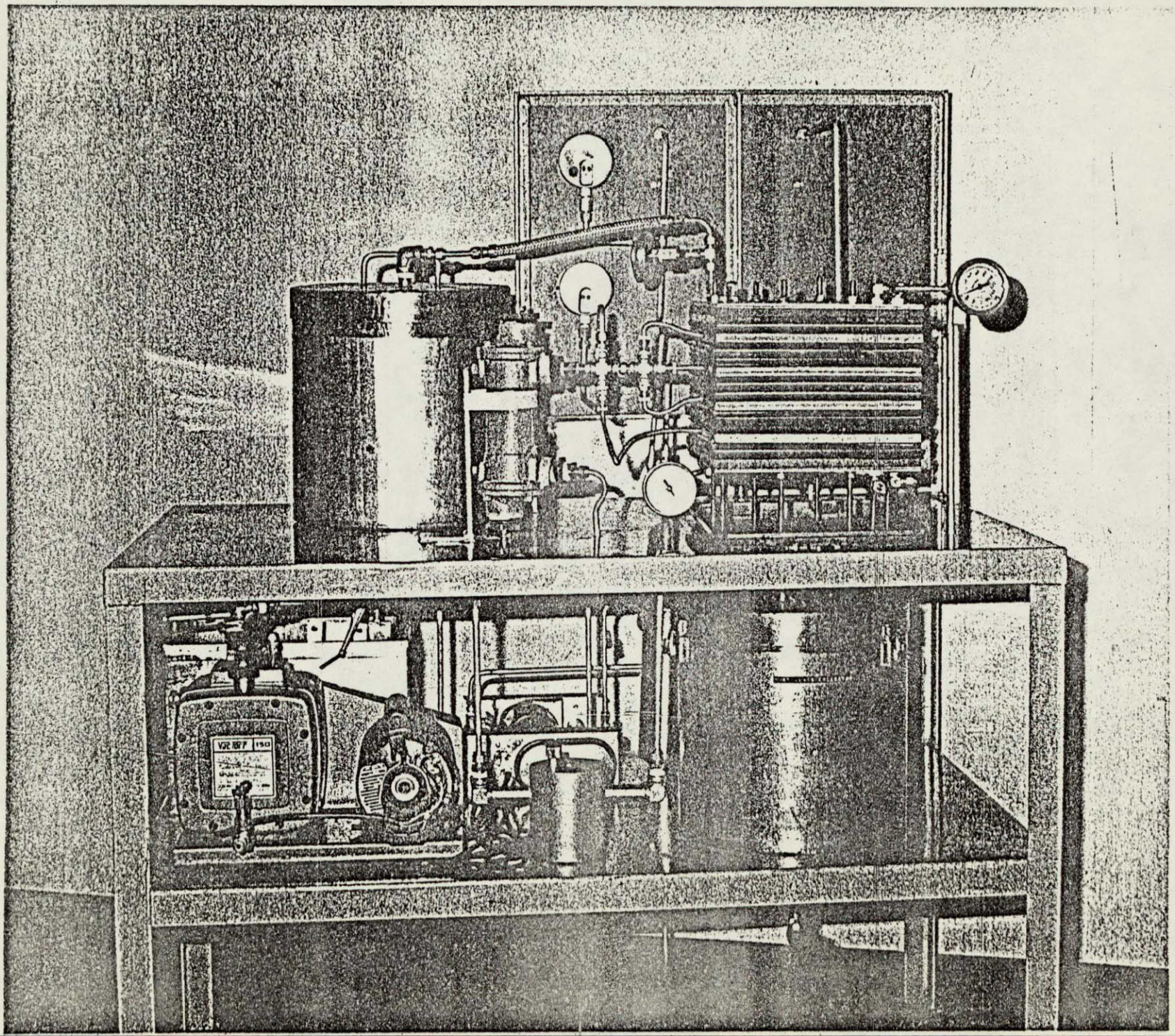
The skid-mount unit is essentially the same as the bench unit except for the replacement of glass components and plastic tubings of the latter with suitable stainless steel components and tubings. In order to maintain cost at a minimum, no attempt has been made to decrease the size and weight of the components used. The components have been located farther apart than they needed to be to allow easy access and flexibility for modification. Any work to make the unit flight suitable is outside the scope of the present program which is investigatory in nature.

For clearer presentation, the system is divided into three sub-systems - the main loop or the charge loop, the heating loop and the water recovery loop - as shown in Figures 16, 17 and 18 respectively. In a flight-suitable unit the heating loop will be replaced with the on-board Freon loop and the water recovery loop will be replaced by the interfacing connection to space vacuum.

As shown in Figure 16, the charge is pumped from its reservoir through a filter cartridge, which may be bypassed depending on the experiment involved, through a control valve and through the charge spacers within the stack and returned to the reservoir and continuously circulated until batch treatment is completed. Charge flow rate and pressure are shown on the display panel. Temperature indicators at the stack show the charge inlet and outlet temperatures.

Figure 17 shows the heating-fluid loop consisting of a constant

Figure 15. Back View of The Skid-Mount Unit



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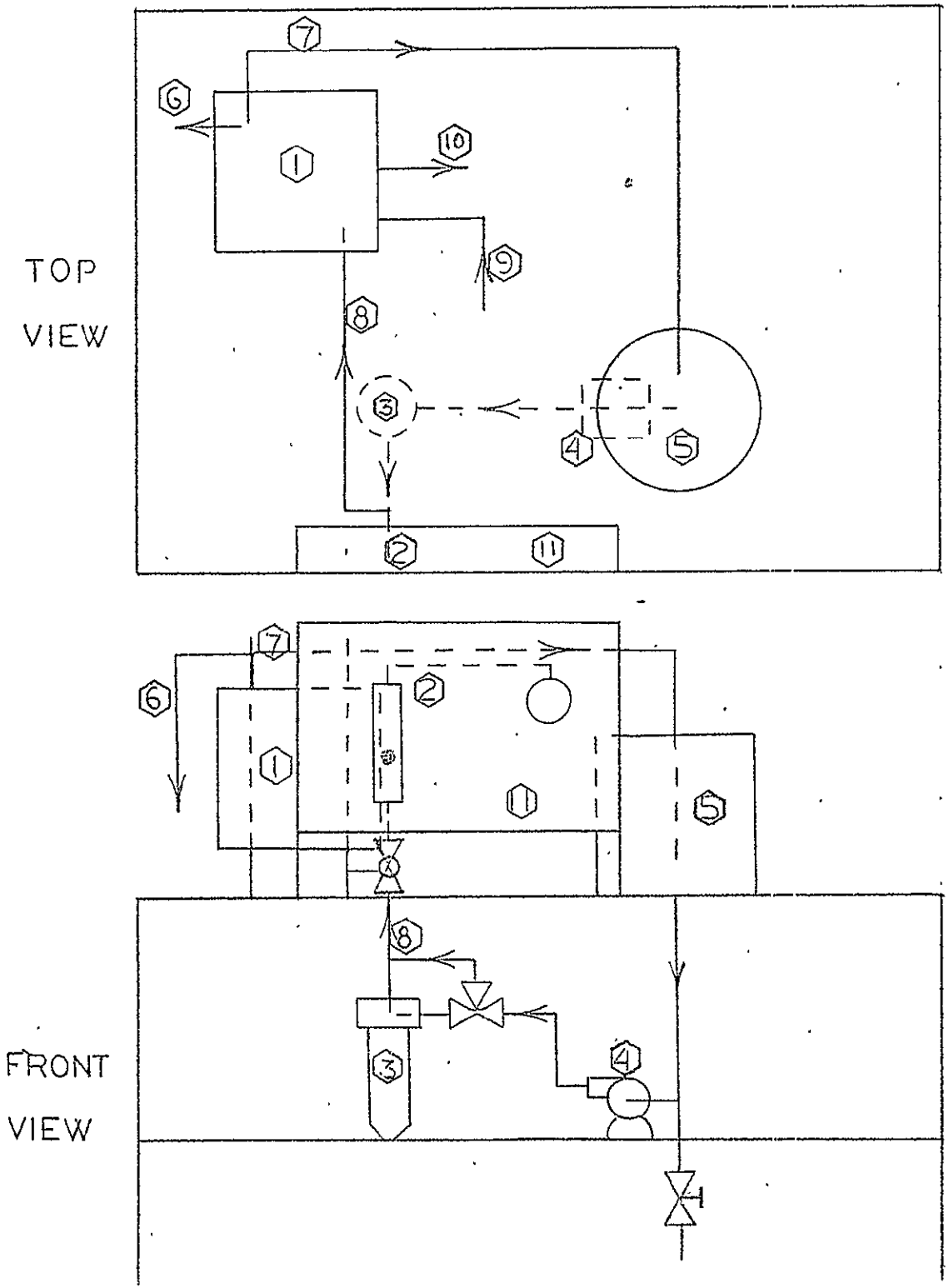
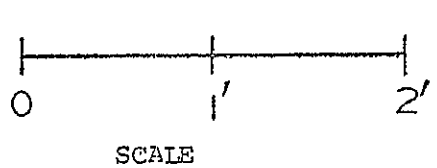


Figure 16. PARTIAL DIAGRAM SHOWING THE CHARGE LOOP

LEGEND:

1. VDR Stack
2. Charge Stream Flowmeter & Gauge
3. Particulate Prefilter
4. Charge Pump
5. Charge Reservoir
6. Hot-Fluid Return Line
7. Charge Return Line
8. Charge In-coming Line
9. Hot-Fluid Incoming Line
10. Vacuum Line
11. Display Panel



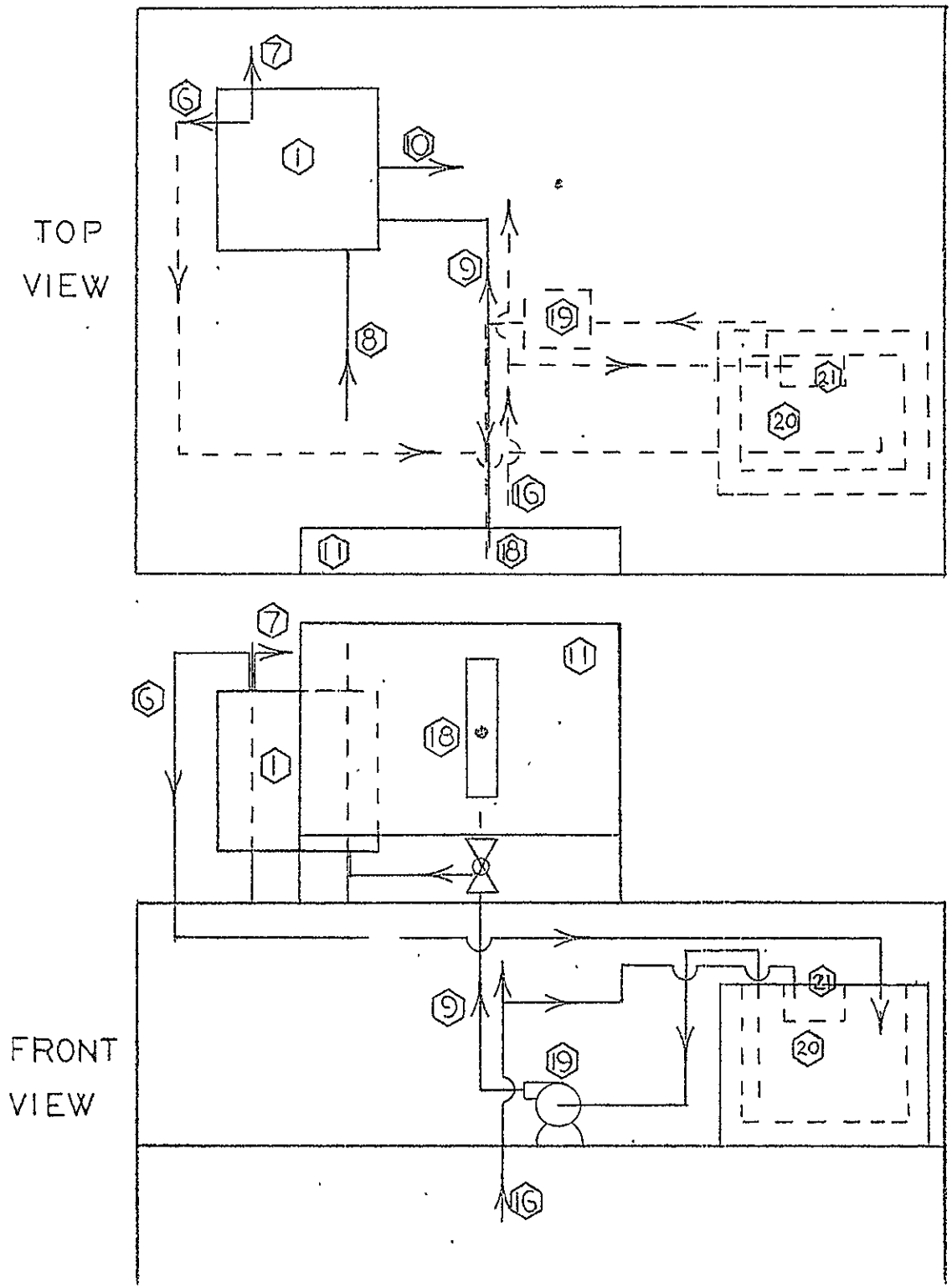
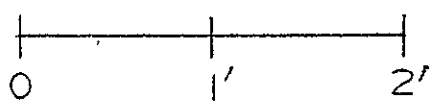


FIGURE 17. PARTIAL DIAGRAM SHOWING THE HOT-FLUID LOOP

LEGEND

1. VDR Stack
6. Hot-Fluid Return Line
7. Charge Return Line
8. Charge Incoming Line
9. Hot-Fluid Incoming Line
10. Vacuum Line
11. Display Panel
16. Cooling-water Incoming Line
18. Hot-fluid Flowmeter
19. Hot-fluid Pump
20. Constant Temperature Bath
21. Hot-fluid Level Control



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temperature bath equipped with a float that allows the in-flow of tap water to replenish any water loss due to evaporation. The heating-fluid pump recirculates the hot water through a control valve, the heating-fluid spacers in the stack and the temperature bath. Heating-fluid flow is also shown in the display panel. Temperature indicators at the stack show the heating-fluid inlet and outlet temperatures.

Figure 18 shows how the permeated water vapor is constantly being removed from the stack. A vacuum pump removes the water vapor which passes through a tap-water-cooled condenser and is collected in a reservoir by gravity. A molecular seive trap located between the pump and the collector prevents the back flow of oil into the collector and reduces water vapor contamination of the vacuum oil. The distillate pressure is displayed in the panel. The subsystem is needed to collect the distillate so that its flux and quality can be monitored, whenever necessary.

The total system was assembled and tested with a combined washwater urine charge for 14 days continuously. Fresh wastewater is added periodically and distillate is removed at the same time. The data collected is shown in Figure 19. At the end of the 14th day 94% of the water had been removed from the wastewater representing the total washwater urine output of a crew of 4 astronauts. The operating conditions are listed below:

Charge flow	= .0029m^3/min (0.75 g.p.m.)
Charge inlet temperature	= 330°K (135°F)
Charge outlet temperature	= 331°K (137°F)
Charge pressure	= 41 megapascal (6psi)
Heating-fluid flow	= .0038m^3/min (1.00 g.p.m.)
Heating-fluid inlet temp.	= 341°K (155°F)
Heating-fluid outlet temp.	= 331°K (140°F)
Distillate absolute pressure	= 1.1-2.1 (megapascal .02 to .04 psi)
Pretreatment or prefiltration	= none
Soap/detergent used	= Witco Chemical Company, Sulframin 1260 slurry
Membrane area	= 0.176m^2 (1.91 ft^2)

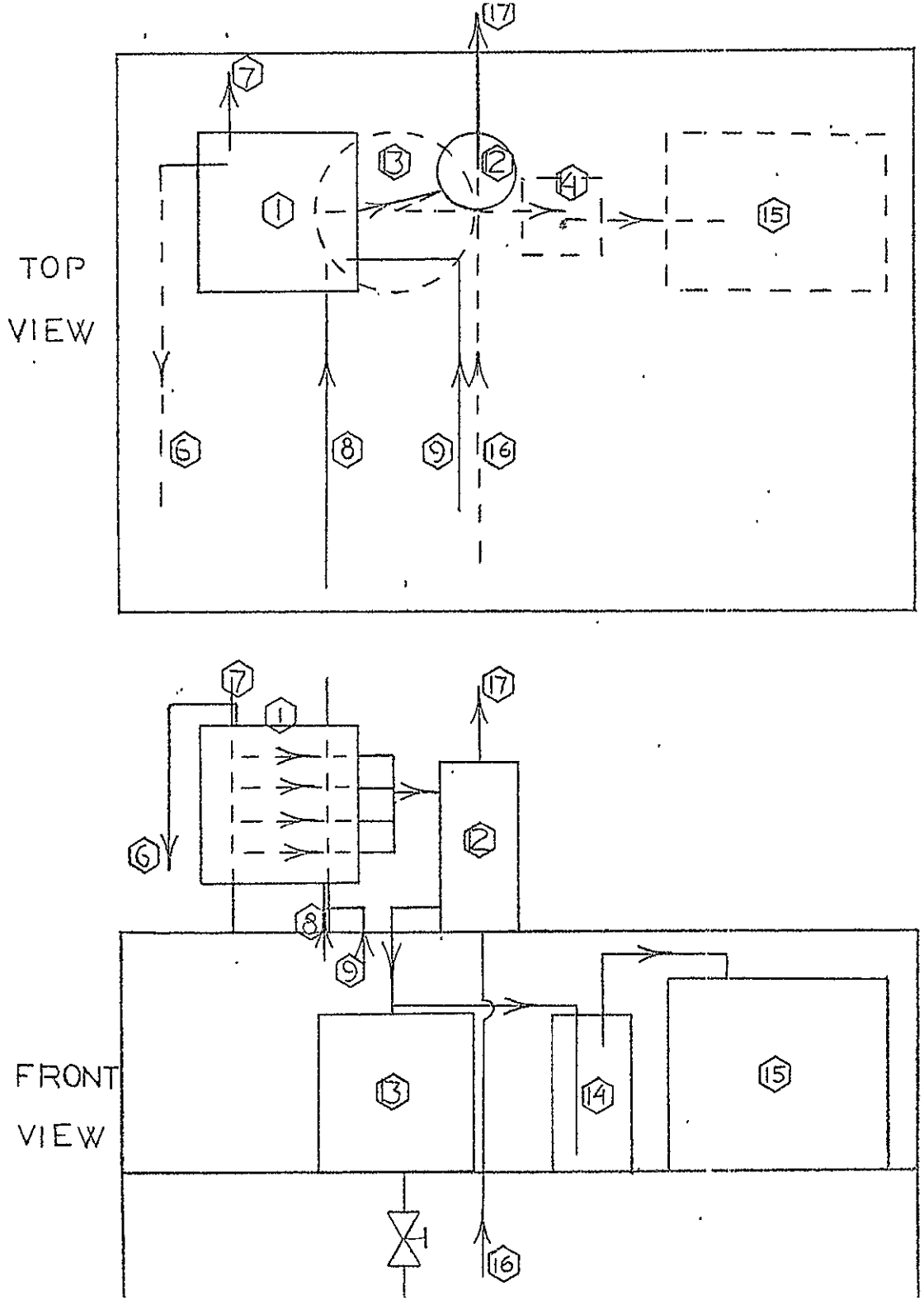

FIGURE 18. PARTIAL DIAGRAM SHOWING THE LOOP VACUUM

LEGEND

1	VDR Stack
6	Hot-Fluid Return Line
7	Charge Return Line
8	Charge Incoming Line
9	Hot Fluid Incoming Line
12	Condenser
13	Distillate collector
14	Cold Trap
15	Vacuum Pump
16	Cooling Water Incoming Line
17	Cooling Water Drain Line

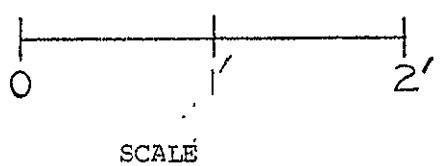

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Figure 19. ACCEPTANCE TEST DATA FOR SKID-MOUNT UNIT

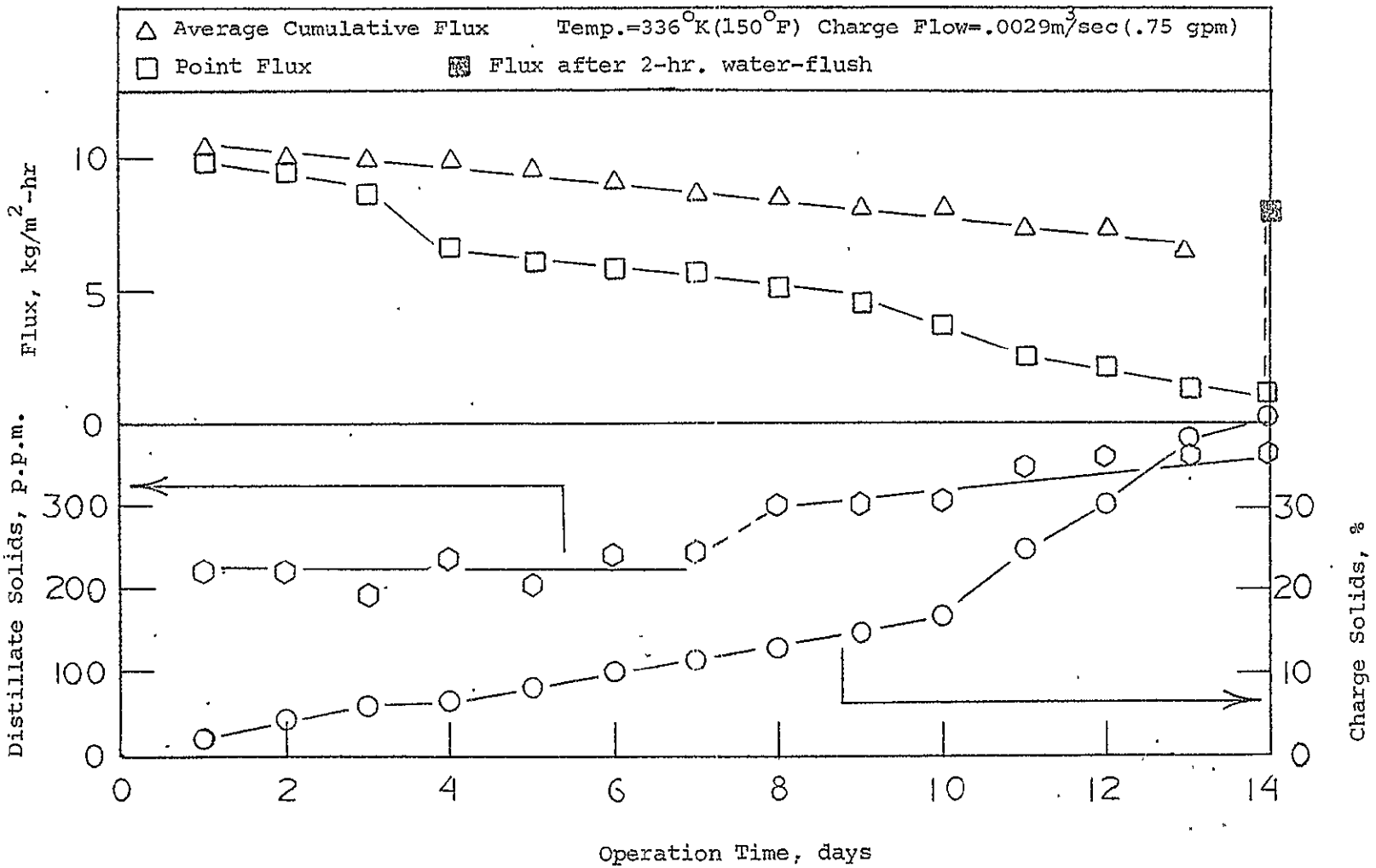


TABLE IV: SUMMARY OF ACCEPTANCE TEST DATA FOR SKID-MOUNT UNIT

Time Elapsed (days)	Total Volume Charged* ($\times 10^{-6}$ m^3)	Charge Total Residue (%, w/w)	Total Volume Permeated ($\times 10^{-6}$ m^3)	Amount Water Removed (% by vol)	Point Flux** (kg/m^2-hr)	Average Cumulative Flux (kg/m^2-hr)
1	30	2.8	15	50	10.7	11.4
2	45	4.4	28	62	9.2	10.6
33	58	5.9	39	67	7.9	9.9
4	69	7.2	49	71	7.5	9.8
5	79	8.6	57	72	5.9	9.1
6	87	9.8	64	74	5.4	8.7
7	94	11.2	71	76	5.2	8.3
8	100	12.9	76.5	76.5	5.0	8.0
9	100	14.4	81.5	81.5	4.5	7.6
10	100	16.7	86	86	3.7	7.5
11	100	24.8	90	90	3.2	7.1
12	100	30.7	93.5	93.5	2.7	7.1
13	100	39.2	95.5	95.5	1.8	6.7
14	100***	44.5	96	96	1.8	---

N.B. *Charged with 3.4 urine-washwater combined waste up to 30 x 10^{-6} m^3 (30 liters) mark daily for the first eight days. No charge added after eighth day.

**Flux taken each morning before adding fresh charge.

***System shut off overnight due to insufficient charge.

VI. SYSTEM EVALUATION

A. System Design

The operating parameters for a VD-HR system have been defined in the previous section. Several improvements over the HSD unit have been incorporated into a nonflight-worthy skid-mount unit. To meet flight worthiness, the various components on the unit will have to be replaced with lighter and smaller components without sacrificing system reliability and safety. Components will also have to be repositioned to minimize occupied space. Electrically operated valves, sensors and switches are needed to minimize in-flight handling of the system by the astronauts. The heating-fluid loop will be replaced by the required interfacing with on-board cooling loop. The condensing-collection subsystem and the vacuum trap and vacuum pump will be replaced by the interfacing connection with space vacuum.

In addition, spare parts may be added in-line to reduce on-board replacement of failing components and increase system reliability. Figure 19 is an example of a VDR design for continuous, automatic operation. The wastewater is collected in a separate waste collection system and stored in a spring-loaded collapsible reservoir. When a particular volume is exceeded, a switch activates solenoid valve SV_1 and the wastewater is squeezed into the batch treatment reservoir until it is filled. At this point another switch activates the three-way solenoid valves SV_1 and SV_2 such that the wastewater charge is continuously circulated around the loop SV_1-SV_2-CRP. At the same time the heating-fluid pump is activated to bring the on-board excess heat to the VD-WR stack where heat exchange occurs through conductive metal plates. SV_3 is then activated and the distillate compartments are connected to space vacuum.

To increase system reliability spare permeation cells may be added

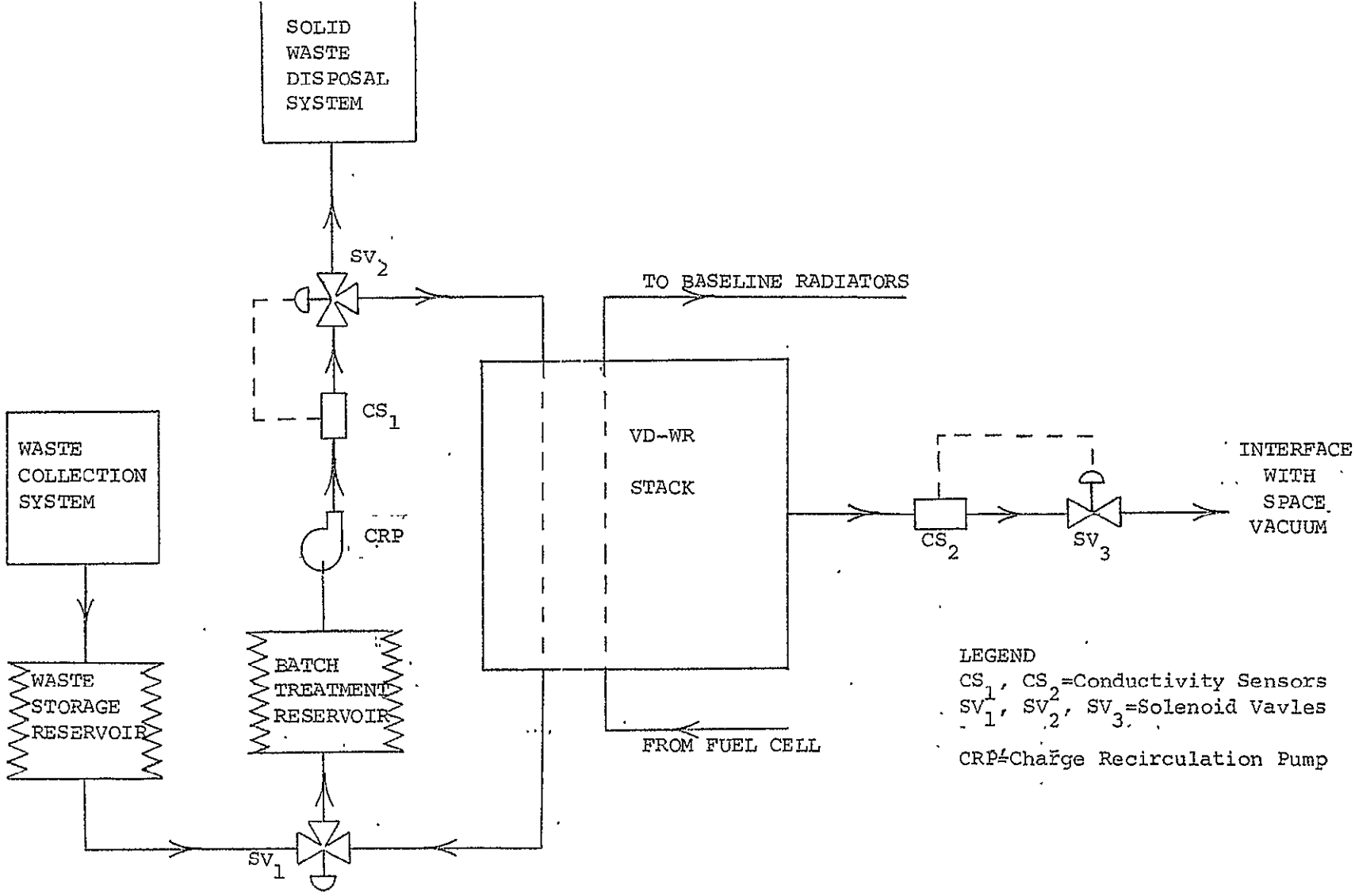


Figure 20. VD-WR System for Waste Rejection On-Board Space Shuttle

to the VDR stack and connected to the primary cells. Wastewater charge is recirculated only through the primary cells, although the heating-fluid may be recirculated through all the cells. Likewise, only primary cells are connected to space vacuum. Such a stack will require external manifolds equipped with solenoid valves and sensors. If malfunction occurs leading to condensate contamination, the sensor will shut off the solenoid valve in the relevant vacuum compartment, as well as the charge inlet solenoid valves belonging to the same cell. This, in turn, sends a signal to the control panel and the charge and condensate solenoid valves of a spare cell will be activated and it will become part of the primary stack. Six spare cells may be included in the stack to form a 10-cell stack. The actual number of cells needed depends on the desired level of reliability and will have to be empirically determined.

The individual cell is equipped with its own sensor and solenoid valves. These sensors and valves should prevent any leaked charge from reaching SV_3. Additional sensors and valves may be added depending on the desired reliability and safety standard.

If no malfunction occurs, waste treatment will continue until the solute weight fraction of the charge reaches 0.40, a level corresponding to 95 percent water removal efficiency. At this point, the conductivity sensor CS_1 shuts off valves SV_1 and SV_3 and diverts the flow through SV_2 such that the waste concentrate is pumped to the solid waste treatment system. When this is completed SV_2 is shut off, SV_1 is activated and the next batch of wastewater is introduced and treated.

B. System Efficiency

The efficiency of the VD-WR system for treating human urine has been repeatedly demonstrated. Long duration tests included HSD's 54-day uninterrupted test in 1966 in which 95 percent of the water was recovered; a shorter test with prefiltration where 98 percent of the water was recovered; several 15-30 day tests by Gulf South and Amicon Company in which 92% of the water was recovered; and the 15-day test under this program in which 94% of the water was recovered. The system can readily recover 95% of the water from wastewater, a level required for a completely closed-loop water system. This represents a 20-fold volume reduction and a 15-fold weight reduction of the on-board wastewater.

C. System Weight and Volume Penalties

The weight and occupied space of a VD-HR prototype are not known, but they can be estimated from known, commercially available components. Table V lists the weights and volumes of presently obtainable non-flight components. These represent the maximum values. Actual values for an on-board unit will be significantly less. Component weight and volume reduction can be achieved by; a) conducting a comprehensive search of commercially available items, b) stripping the items of all nonessential parts and, c) incorporation of special components made available by space technology.

From Table V, the maximum system weight is calculated to be 64.7kg (142lb) fixed weight. No expendable will be needed. The system occupied space is similarly calculated to be $0.678m^3$ ($4140\ in^3$). Taking into account wasted space between some components, the VDR unit is expected to fit into a box of 0.36m x 0.36m x 0.76m (14in x 14in x 30in). With the application of the aforementioned reduction techniques these values can be decreased by an estimated 30%.

Comparison of these values with the on-board waste storage may be made. Assuming an average crew of four astronauts, the daily amount of

of urine produced is 0.006m^3 (1.58 gal) and the daily amount of washwater is 0.008m^3 (2.11 gal). For an average mission duration of 14 days, the total wastewater produced is 0.196m^3 (51.8 gal). The corresponding weight is 225kg (496lb). The application of VDR can reduce these values to a maximum of 0.0098m^3 (2.59gal) and 12.2kg (26.9lb). Adding these to the estimated maximum weight and volume penalties of the VDR, the values become 0.108m^3 (285gal) and 76.9kg (169lb), respectively. These compare favorably with the weight and volume penalties of on-board storage -- 45% space savings and 66% weight savings even if the weight and volume of the storage tank is ignored.

The calculations above refer to the re-entry weight and volume savings. The affect of the VD-HR on launch weight is different. (Launch volume is unaffected because cabin space must be provided for storing the wastewater that will be produced through the course of the mission.) At launching, the VD-HR will provide supplemental cooling resulting in a savings if waste storage is intended. Whether such an additional weight is acceptable may depend on various other factors not known to this investigator. The VDR will provide supplemental cooling resulting in a savings of baseline radiator weight which may be significant. Additional weight from waste storage at re-entry requires additional fuel which is carried within the shuttle. This difference may also be significant. In addition, the accumulation of waste within the cabin may take up valuable space which may not be acceptable.

The contribution of the VD-HR unit will increase the advancement in the technology involved. It will also become more significant if crew size or mission duration are increased since any increase in the weight and volume penalties will be only a fraction of the corresponding increase in waste storage weight and volume penalties.

D. Energy Requirement

The energy requirement of the VD-HR is equal to the pumping energy required to operate the charge pump, the heating fluid pump and the conductivity sensors and solenoid valves. Based on a charge flow of $0.0029 m^3/min$ (.75gpm) and a heating-fluid flow of .0039 (1.0gpm) and corresponding pressure drops of 55 megapascal (8 psi) and 41 megapascal (6 psi), respectively; the total theoretical energy required to operate the pumps is 14.6 watts. Assuming a pump efficiency of 60% this becomes 24.4 watts. The energy required for the instruments is estimated as 10 watts. The total power consumption of the VD-HR is then 34.4 watts.

TABLE V SYSTEM FIXED WEIGHT AND VOLUME PENALTIES

(These are Non Flight Components)

SYSTEM COMPONENTS	NUMBER NEEDED (include spares)	MAXIMUM WEIGHT Kg	(lb)	MAXIMUM VOLUME $m^3 \times 10^{-3}$	(in^3)
1. Treatment Reservoir	2	9.1	(20)	12.00	(732)
2. Charge Pump	2	5.0	(11)	3.68	(224)
3. Hot-fluid Pump	1	2.5	(5.5)	1.84	(112)
4. Hot-fluid Tank	1	1.0	(2.2)	0.82	(50)
5. Permeation Cell	10	22.1	(48)	35.4	(2160)
6. Stack Frame	1	2.27	(5.0)	0.16	(10)
7. Charge Manifold	1	5.0	(11)	0.98	(60)
8. Vacuum Manifold	1	3.3	(7.3)	0.74	(45)
9. Valves	3	.73	(1.6)	1.31	(80)
10. Sensors	3	1.5	(3.3)	1.64	(100)
11. Skid Frame	1	5.2	(11)	3.93	(240)
12. Panel	1	2.0	(4.4)	3.28	(200)
13. Piping & Fittings	-	2.3	(5.1)	0.49	(30)
14. Central Relay	1	2.73	(6.0)	1.57	(96)
TOTAL		64.7 Kg	(142) (lb)	0.678 m^3	(4140) (in^3)

VII. RECOMMENDATIONS FOR FUTURE STUDIES

1. Defining the need for the VD-HR

The feasibility of the VD-HR for Shuttle Application has been examined. All indications are that the system is feasible. The immediate area for future studies lies in the examination of Shuttle Systems to define more exactly the extent of the need or advantage of a waste-alleviation and supplemental cooling unit. Advantages of the VD-HR as opposed to alternative means of waste-alleviation and provision of supplemental cooling should be examined through a study of the alternative means.

2. Feasibility Studies

It is concluded, in this report, that the feasibility of the VD-HR lies in the interface with on-board heat source and with space vacuum. Future studies should examine these interfaces in detail. Sufficient confidence in the feasibility of such interfaces must precede the fabrication of a prototype.

3. Preprototype Design Studies

Material selection and component selection have been largely ignored in the present program. In preparation for a prototype, a survey of existing commercially available components should be made with emphasis on minimum weight, volume and energy penalties and on maximum life, reliability and safety. Wherever feasible and necessary, the components should be stripped of nonessential parts or suitably modified. The design of a preprototype should be made based on these components.

4. Water Reclamation Loop

The alternative of reclaiming part or all of the treated water for reuse may be needed. This could be an end in itself or it could be a step towards a complete water reclamation system for use during missions

of extended duration. The design of this loop is outlined in the Appendix. Its development is another important area for future work.

5. Design and Fabrication of Prototype

Eventually, the design and fabrication of the prototype VD-HR with or without the alternative water reclamation loop should be performed. It may be equally important to develop, design and fabricate a VD-WR with no provision for over-board venting where the sole application is a completely independent water reclamation system.

VIII. APPENDIX

An Alternative Loop for Water Reclamation

VD-WR for Water Reclamation

It may be desirable to recover the water separated from the waste-water for on-board usage. The answer lies in the original VD-WR concept. Figure 21 is a schematic diagram of such a system designed by Ionics, Inc.

Briefly, the VD-WR stack calls for the substitution of the vacuum compartments of the VD-HR stack with porous plate condensers. Figure 22 is a diagram of such a stack consisting of four normally operating cells and six spare cells.

As seen in Figure 22, cells #1 through #4 form the normal stack. The urine charge is recirculated only through these cells. Each cell is equipped with a conductivity sensor in the condensate line. If a malfunction occurs leading to condensate contamination, the sensor will be activated and the solenoid valves in the condensate, as well as the charge lines belonging to the same cell, will be shut off. This, in turn, sends a signal to the control panel and the next cell, in this case cell #5, will be included in the new treatment stack by activating the charge and condensate solenoid valves of cell #5.

The condenser is formed by imbedding a cooling coil inside a sandwich of two porous plates of suitable porosity. This has been successfully demonstrated by HSD. The portion of the plates not exposed to the diffusing vapor is covered by a nonporous metal to form a condensing chamber as shown in Figure 23. Water condenses at the cold porous plate and is held within by surface tension. A recirculating fan promotes forced convention in the gap to reduce boundary layer resistance to vapor diffusion and effectively moves the vapor by mixing from the membrane to the condenser. The accumulation of noncondensables inside the vapor gap is prevented by

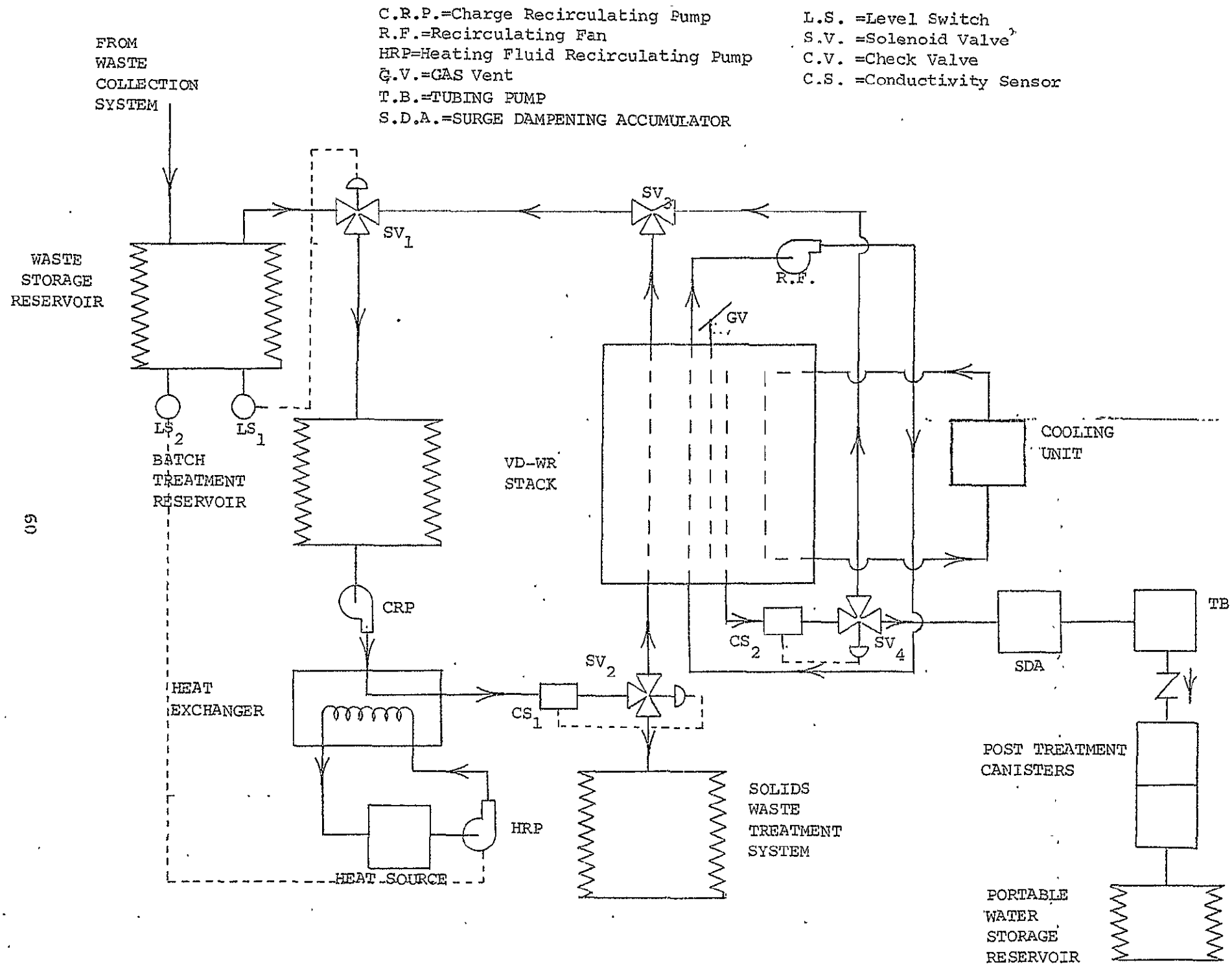


Figure 21. VD-WR SYSTEM TO RECLAIM THE PERMEATED WATER

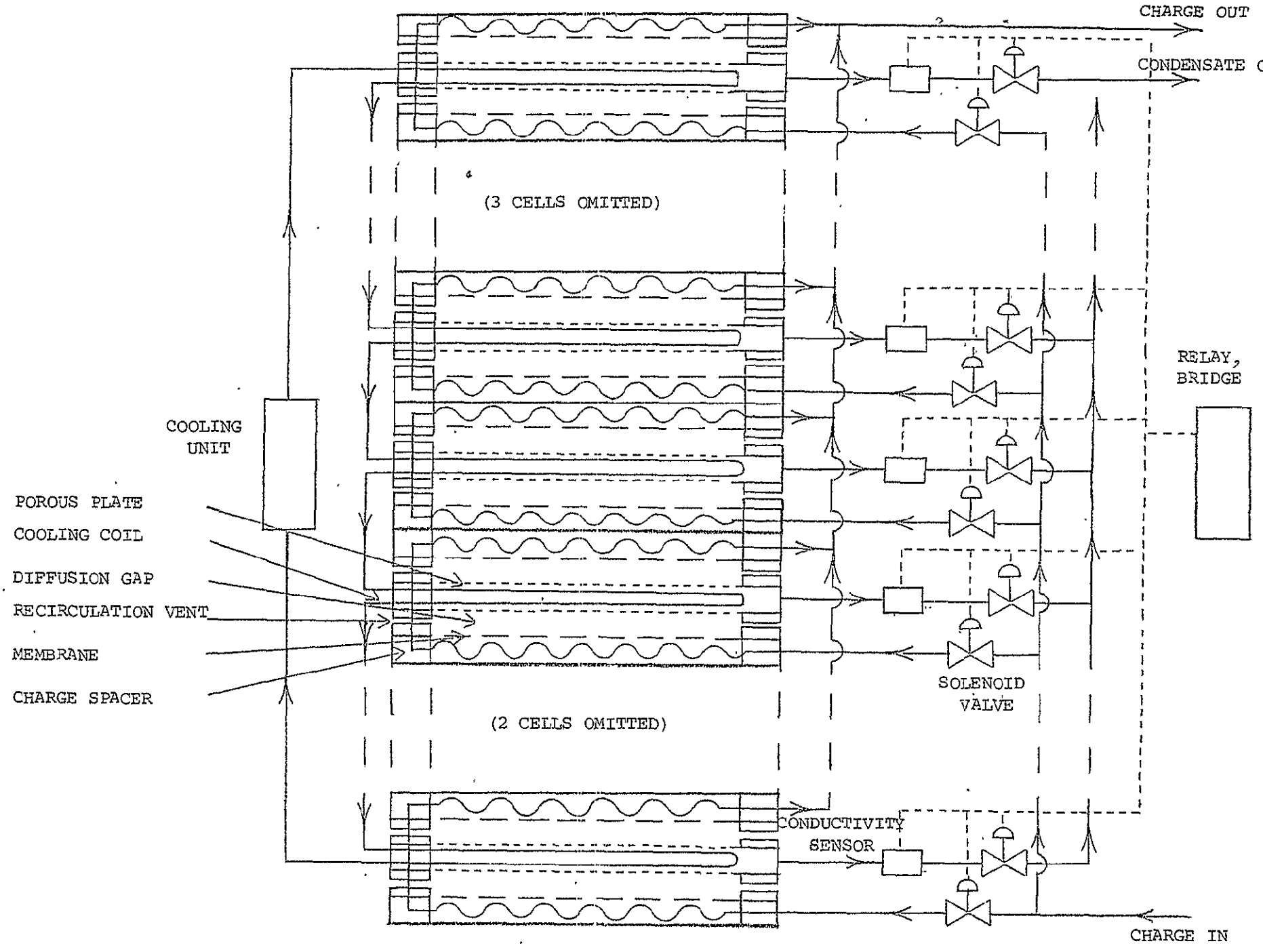
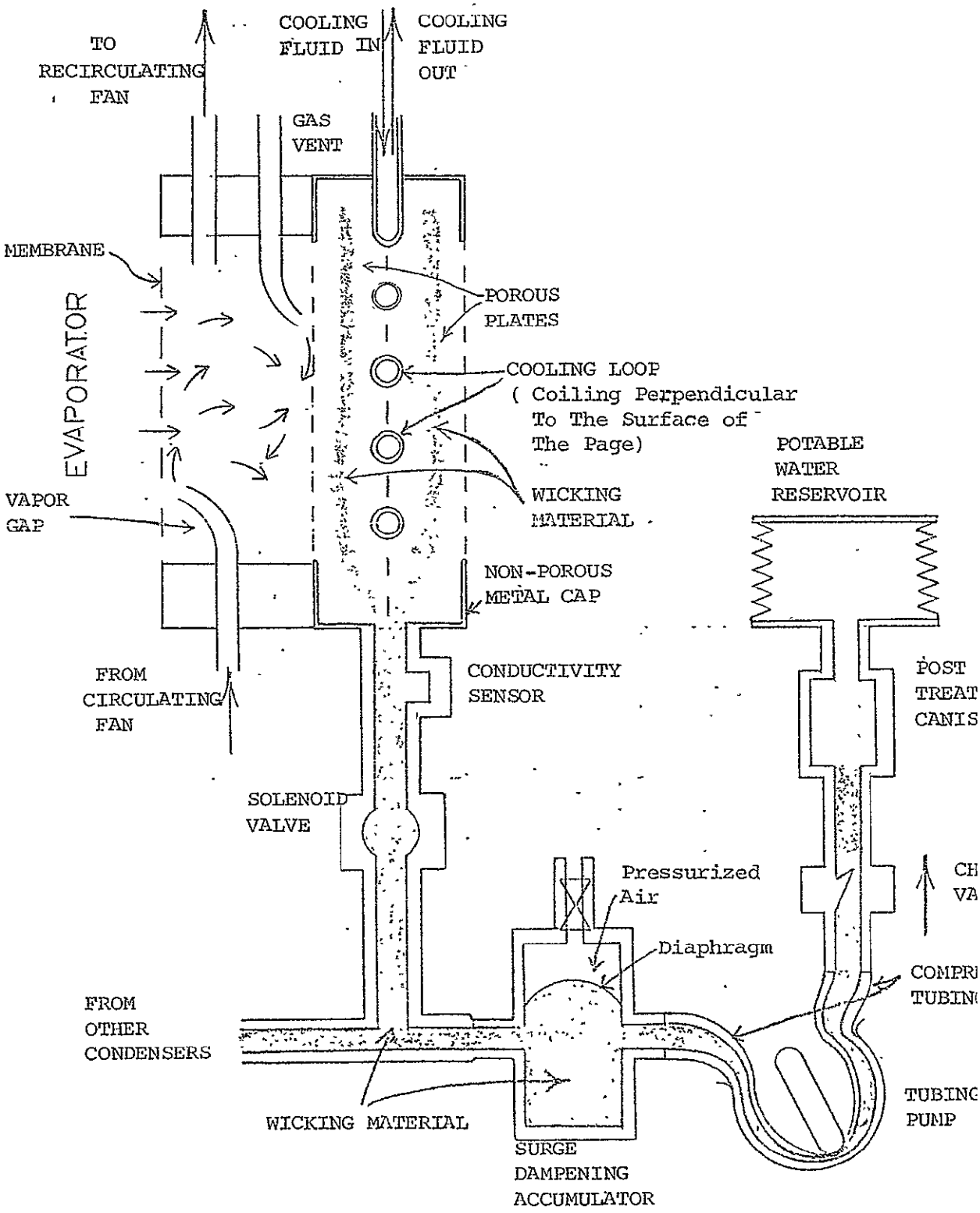


Figure 22. A 10-CELL VD-WR STACK


TO RECIRCULATING FAN
COOLING FLUID IN
COOLING FLUID OUT
GAS VENT
MEMBRANE
EVAPORATOR
POROUS PLATES
COOLING LOOP
(Coiling Perpendicular To The Surface of The Page)
WICKING MATERIAL
VAPOR GAP
NON-POROUS METAL CAP
POTABLE WATER RESERVOIR
FROM CIRCULATING FAN
CONDUCTIVITY SENSOR
POST TREAT CANIS
SOLENOID VALVE
Pressurized Air
Diaphragm
FROM OTHER CONDENSERS
WICKING MATERIAL
SURGE DAMPENING ACCUMULATOR
TUBINC PUMP

means of a cabin vent through which the noncondensables, some ammonia and certain volatile organics diffuse.

The condensate in the porous plate is removed through wicks. Conductivity sensors constantly monitor the quality of the product water leaving the condenser. A conductivity reading exceeding 1450 μmho/cm, approximately equivalent to a sodium chloride level of 1000 ppm, indicates cell malfunction. When such a level is detected, a signal is sent to the central control panel which shuts off a solenoid valve a short distance downstream and the charge inlet valve of the malfunction cell, and switches on the corresponding valves of the next spare cell. This system of installed spares effectively changes permeation cells without requiring actual on-board maintenance by the astronauts.

The condensate from all functioning cells is combined and picked up by wicking. The wick is contained in flexible tubing and the assembly is passed through a tubing pump with an off-centered rotating cam. The pump pushes the condensate through post-treatment canisters, through a check valve, into a spring-loaded collapsible reservoir. An in-line accumulator dampens the surging effect of the pump, and together with the wick, minimizes any unusually large transient, negative pressure effect on the porous-plate condensers. This effectively prevents gaseous material from being sucked into the condensing assembly.

National Aeronautics and
Space Administration
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Moffett Field, California
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NASA

Reply to Attn of NAS 2-7651
ATL:202-3

September 21, 1977

NASA Representative
Scientific & Technical Information Facility
P.O. Box 8757
Baltimore/Washington International Airport
Maryland 21240

Subject: Transmittal of Contractor Report: "Water Vapor Diffusion Membrane Development," final report, Dated July 26, 1977 by Michael K. Tan, Ionics, Incorporated, 65 Grove Street, Watertown, Massachusetts, 02172.

Reference: Program Code 199-73-02-11

The subject report prepared under Contract NAS 2-7651 has been reviewed at Ames and is recommended for release in STAR as CR-152037.

Ralph W. Lewis
Chief, Library Branch

Enclosure:
1 cy subject report

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